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MANAGEMENT BRIEF

Using Tag-Return Models to Estimate the Number of Times Fish Are Captured in Fisheries with High Catch-and-Release Rates

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Abstract
Exploitation rates are often estimated using tag-return studies. However, in fisheries with a catch-and-release component, exploitation rate or fishing mortality may not be the most important metric of interest. Instead, angler catch rates (e.g., fish caught per hour), total catch (including fish that are harvested or released), or the average number of times an individual fish is caught may be a better measure of fishery performance. However, if anglers remove tags from fish before release, then catch estimates will be negatively biased because tag removal will not be accounted for. In this study, maximum likelihood estimation methods were used to estimate catch in fisheries with high rates of catch and release. Right-censored models were used to accommodate tags that may or may not be removed by anglers. Model-derived maximum likelihood estimates of mean catch were relatively unbiased under two simulated fishery scenarios. There was a nonlinear, positive relationship between the percentage of tags that were removed from fish before release and the standard error of estimated mean catch. Although the models performed well at estimating catch in the simulations, more study is needed to evaluate how possible violation of model assumptions can affect catch estimates.

Exploitation rate or fishing mortality is an important metric for sustainable management of naturally reproducing fish populations. Absolute or relative exploitation rate can serve as the response variable in research evaluating hatchery programs (e.g., Dillon et al. 2000; Koenig and Meyer 2011) or as a management objective for recreational fisheries. Catch-and-release recreational angling has been increasing in popularity over the last several decades (Cowx 2002; Gaeta et al. 2013). Thus, methods for estimating exploitation rate in recreational fisheries using reward tag-return studies (Pollock et al. 1991, 2001, 2002; Meyer et al. 2012) may not be appropriate when the goal of the fishery is not necessarily harvest. Additionally, when catch-and-release regulations are in effect, exploitation is seldom of interest, and other metrics, such as total catch or the average number of times a fish is caught, may more valuable for evaluating the performance of the fishery.

Exploitation rate is overestimated when fish that are caught and released are treated as harvested in tag-return models (Bacheler et al. 2008). If it is assumed that catch and harvest are identical, then estimates of exploitation rate can exceed 100% when a large majority of fish are caught and released or when many fish are caught multiple times (e.g., Schill et al. 1986). Conversely, estimating true exploitation rate (i.e., only harvested fish) in fisheries with high catch-and-release rates can misinform management of recreational fisheries. For instance, a hatchery program may be deemed unsuccessful if the exploitation rate is low; however, if anglers are releasing a large proportion of fish, the program may be successful at providing a robust fishery with catch rates suitable to anglers.

The traditional Brownie model (Brownie et al. 1985) has been extended to estimate fishing and natural mortality for fisheries with both harvest and catch and release (e.g., Smith et al. 2000; Jiang et al. 2007; Bacheler et al. 2008; Kerns et al. 2015). However, fish that were released with tags intact in those studies were either ignored, or only data from the

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first capture were used in the analysis. Additionally, I am unaware of any published studies where methods have been described to estimate catch using tag-return models in fisheries with high catch-and-release rates where tags may be removed or left intact. The objectives of this study were to describe and evaluate a statistical model to estimate the number of times fish are caught when anglers may or may not remove reward tags.

METHODS

Modeling catch.—The general approach used here to estimate the average number of times fish were caught (hereafter, mean catch), including fish that were caught and released after their tags were removed, was to treat such observations as right-censored. Mean catch should not be confused with catch rate, which represents the number of fish caught per unit of angling effort and cannot be estimated using tag-return models without an independent estimate of angling effort. Maximum likelihood estimation was used to estimate mean catch using the right-censored models. Although multiple distributions can be used to derive maximum likelihood estimates with right-censored data, the Poisson and negative binomial distributions were used to model catch. The Poisson distribution is commonly used to model count data where the variance is equal to the mean, and the negative binomial distribution allows for dispersion that is different from the mean. The Poisson probability mass function is defined (Rice 2007) as

$$f(x|\lambda) = P(X = x) = \frac{\lambda^x e^{-\lambda}}{x!}, \tag{1}$$

where λ is the rate parameter to be estimated and represents mean catch in this application, X is a random variable, and values for x are the observed data. The negative binomial probability mass function is defined (Rice 2007) as

$$\begin{aligned} f(x|m,k) &= P(X = x) \\ &= \left(1 + \frac{m}{k}\right)^{-k} \frac{\Gamma(k+x)}{x!\Gamma(k)} \left(\frac{m}{m+k}\right)^{x}, \end{aligned} \tag{2}$$

where m is the mean, k is the dispersion parameter, and Γ is the gamma function (Rice 2007). The likelihood function for the Poisson distribution is

$$L(\lambda|x_i) = \prod_{i=1}^{n} \left(\frac{\lambda^{x_i} e^{-\lambda}}{x_i!}\right), \tag{3}$$

where x_i is the number of times the ith tag was reported and n is the total number of tags released. The likelihood function for the negative binomial distribution is

$$L(m,k|x_i) = \prod_{i=1}^{n} \left(1 + \frac{m}{k}\right)^{-k} \frac{\Gamma(k+x_i)}{x_i!\Gamma(k)} \left(\frac{m}{m+k}\right)^{x_i}. \tag{4}$$

The Poisson function can be maximized over λ, and the negative binomial function can be maximized over m and k to estimate mean catch when all tags are left intact before release. However, this will not provide an unbiased estimate of mean catch when some tags are removed before release (i.e., data are right-censored).

If a tag is removed from a fish before it is released, then the actual number of times the fish is caught (X_i) is greater than or equal to the number of times its tag is reported (c_i). Thus, if a tag is removed from a fish that is released, then the probability that the true catch exceeds reported catch (Saffari and Adnan 2011) is

$$P(X_i \geq c_i) = \sum_{j=c_i}^{\infty} P(X_i = j) = 1 - \sum_{j=0}^{c_i - 1} P(X_i = j). \tag{5}$$

If a fish is released with the tag intact or a tagged fish is harvested, then $X_i = x_i$. Therefore an indicator variable d_i can be defined, such that

$$d_i = \begin{cases} 1 \text{ if } X_i \geq c_i, \\ 0 \text{ otherwise.} \end{cases}$$

The general likelihood that includes right-censored observations can then be written (Saffari and Adnan 2011) as

$$L(\theta|d_i, x_i, c_i) = \prod_{i=1}^{n} \left[(f\{x_i\})^{1-d_i} (1 - F\{c_i - 1\})^{d_i} \right], \tag{6}$$

where F represents the cumulative distribution function used in the likelihood and θ represents a parameter or parameters to be estimated. Thus, the Poisson likelihood with right-censored observations can be written as

$$L(\lambda|d_i, x_i, c_i) = \prod_{i=1}^{n} \left[\left(\frac{\lambda^{x_i} e^{-\lambda}}{x_i!}\right)^{1-d_i} \left(1 - \sum_{j=0}^{c_i-1} \left\{\frac{\lambda^{c_i} e^{-\lambda}}{c_i!}\right\}\right)^{d_i} \right], \tag{7}$$

and the negative binomial likelihood with right-censored observations can be written as

$$L(m,k|d_i,x_i,c_i) = \prod_{i=1}^{n} \left[\begin{array}{c} \left\{ \left(1+\frac{m}{k}\right)^{-k} \frac{\Gamma(k+x_i)}{x_i!\Gamma(k)} \left(\frac{m}{m+k}\right)^{x_i} \right\}^{1-d_i} \\ \times \left\{ 1 - \sum_{j=0}^{c_i-1} \left(1+\frac{m}{k}\right)^{-k} \frac{\Gamma(k+c_i)}{c_i!\Gamma(k)} \left(\frac{m}{m+k}\right)^{c_i} \right\}^{d_i} \end{array} \right]. \tag{8}$$

The likelihood functions can then be maximized or the negative log of the likelihood functions can be minimized to estimate mean catch.

There were several assumptions using the version of the model described in this study. The first assumption was that all tags are reported. In practice, this assumption can be mitigated for if a reporting rate is known or estimated (Pollock et al. 2001, 2002; Meyer et al. 2012) but still requires that all fish from which tags are removed are reported. Additionally, the model-derived estimator also has the same assumptions common to most tagging studies, such as no tag loss other than anglers removing tags, tagging does not affect survival or catchability, and complete mixing of tagged fish (Pollock et al. 2001).

Simulation.—A simulation study was conducted to evaluate the properties of mean catch estimates using simulated data from a hypothetical fishery where caught fish were retained (harvested) or released with tags either intact or removed. Two fishery scenarios were evaluated using two distributions of mean catch. In both scenarios 500 fish were tagged and released in the hypothetical fishery. Under the first fishery scenario, the number of times each fish was caught was drawn from the Poisson distribution with a rate parameter (λ) of 9.7 (Figure 1). This parameter was selected based on Schill et al. (1986) where the authors estimated that Yellowstone Cutthroat Trout *Oncorhynchus clarkii bouvieri* in the Yellowstone River were caught and released 9.7 times on average over the duration of the study. In the second simulated fishery, the number of times each fish was caught was drawn from the negative binomial distribution where the scale (m) and the shape parameter (k) were equal to two (Figure 1). Parameters used to generate catch with the negative binomial distribution were chosen arbitrarily to represent a fishery where mean catch was relatively low. The mean of the simulated data represents the actual known mean number of times each fish was caught and are the data that are observed when no tags were removed from fish. If anglers remove tags from fish during the catch-and-release process, these data will never be observed.

In both hypothetical fisheries, 10–80%, in increments of 10%, of fish that were caught were released with tags removed. The remaining fish were either harvested, released with tags intact, or not caught at all. Fish with tags removed were randomly selected with equal probability. The catch occasion when the tag was removed was given an equal probability over all integers between the first and the last capture. It was assumed that anglers reported all tagged fish that were caught and whether they released the fish after removing the tag (i.e., $d_i = 0$ or $d_i = 1$). Thus, the data used in the analysis were two vectors of numbers, the first vector was the number of times a tag was reported and the second was a vector of ones and zeros indicating whether the tag had been removed or left intact before release, respectively.

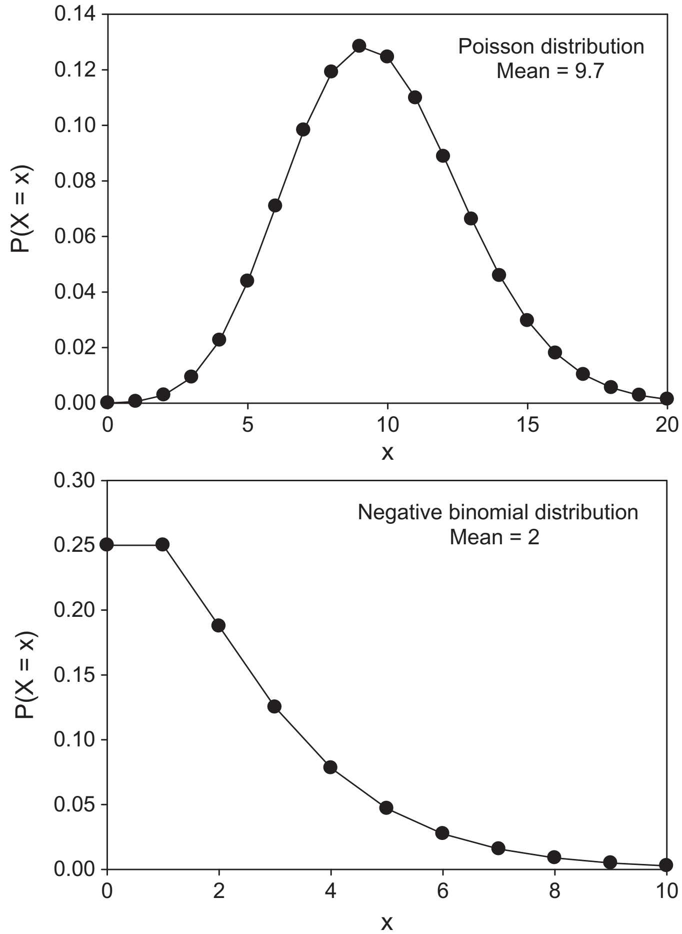

FIGURE 1. Probability mass function for the Poisson distribution with a rate parameter of 9.7 (top panel) and a negative binomial distribution with shape parameter of 2 and scale parameter of 2 (bottom panel). These functions were used to generate simulated catch data where x represents the number of fish caught, and $P(X = x)$ represents the probability that a fish would be caught x times.

Maximum likelihood estimates were obtained by minimizing the negative log of equation (7) for the scenario where catch was drawn from the Poisson distribution and using equation (8) where catch data were generated from the negative binomial distribution. Two additional estimators of mean catch were also evaluated. The first estimator (i.e., the naïve estimator) was simply calculated as the mean number of times each tag was reported with no attempt to account for tag removal. The second estimator was calculated as the mean number of times tags were reported using only data from fish whose tags were not removed over the duration of the season (i.e., uncensored observations).

The process of generating data and estimating mean catch using the three estimators was repeated 1,000 times for both fishery scenarios and every level censoring. This resulted in sampling distributions consisting of 1,000 estimates of mean catch. To assess the bias of each estimator, the mean of each sampling distribution using observed data were compared with mean catch that was known in the simulation. To evaluate the effect of censoring on the variance of model-derived estimates, the standard deviation of the sampling distribution was estimated for the model-derived estimator. The standard deviation of the sampling distribution represents the empirical standard error of the estimator (Efron and Tibshirani 1993). Simulations and statistical analyses were conducted using the R statistical computing language (R Development Core Team 2015).

RESULTS

Model-derived maximum likelihood estimates were relatively unbiased at estimating mean catch under both fishery scenarios (Table 1). The maximum absolute percent bias observed was 0.09% when the Poisson distribution was used to generate catch data and 0.11% when the negative binomial distribution was used. The amount of bias under both catch generating distributions was unrelated to the simulated level of censoring. There was a nonlinear, increasing relationship between the percentage of tags that were removed from fish before release and the SE of the estimated mean catch using the model-derived estimators (Figure 2).

When only observed data were used to estimate mean catch, bias varied from 4.5% to 35.8% under the Poisson data generating process and from 3.1% to 25.03% using the negative binomial distribution. Bias increased as the percent of tags removed increased (Table 1). When only uncensored observations (i.e., data from tags that were left intact before release) were used to estimate mean catch, bias varied from 0.004% to 0.05% when the Poisson distribution was used to generate catch data and from 2.7% to 49.8% when the negative binomial distribution was used to generate the data. Similar to when all observed data were used, bias increased as the percentage of tags removed increased (Table 1).

TABLE 1. Simulated actual and mean number of times each tagged fish was captured under two tag-return-study scenarios where fish were harvested or released with tags removed or left intact at time of release. Three estimators were used: (1) model-derived, (2) using only observed data, and (3) using only data from fish that were released with tags left intact (uncensored observations). Simulations allowed the proportion of tags removed to vary by increments of 0.1 from 0.1 to 0.8, and two mean-catch scenarios were simulated. The first scenario generated mean catch estimates using a Poisson distribution and assuming the mean catch was 9.7, whereas the second scenario used a negative binomial distribution and assumed a mean catch of 2.0.

Proportion removed	Actual mean	Model-derived	Observed data	Uncensored observations
Poisson distribution (mean catch = 9.7)				
0.1	9.70	9.70	9.26	9.70
0.2	9.71	9.71	8.84	9.71
0.3	9.70	9.70	8.40	9.70
0.4	9.69	9.69	7.95	9.69
0.5	9.69	9.68	7.52	9.68
0.6	9.70	9.70	7.09	9.70
0.7	9.71	9.71	6.65	9.71
0.8	9.70	9.70	6.22	9.70
Negative binomial distribution (mean catch = 2.0)				
0.1	2.00	2.00	1.94	1.95
0.2	2.00	2.00	1.87	1.88
0.3	2.00	2.00	1.81	1.80
0.4	2.00	2.00	1.75	1.72
0.5	1.99	1.99	1.68	1.60
0.6	2.01	2.00	1.63	1.46
0.7	2.00	2.01	1.57	1.27
0.8	2.00	2.00	1.50	1.00

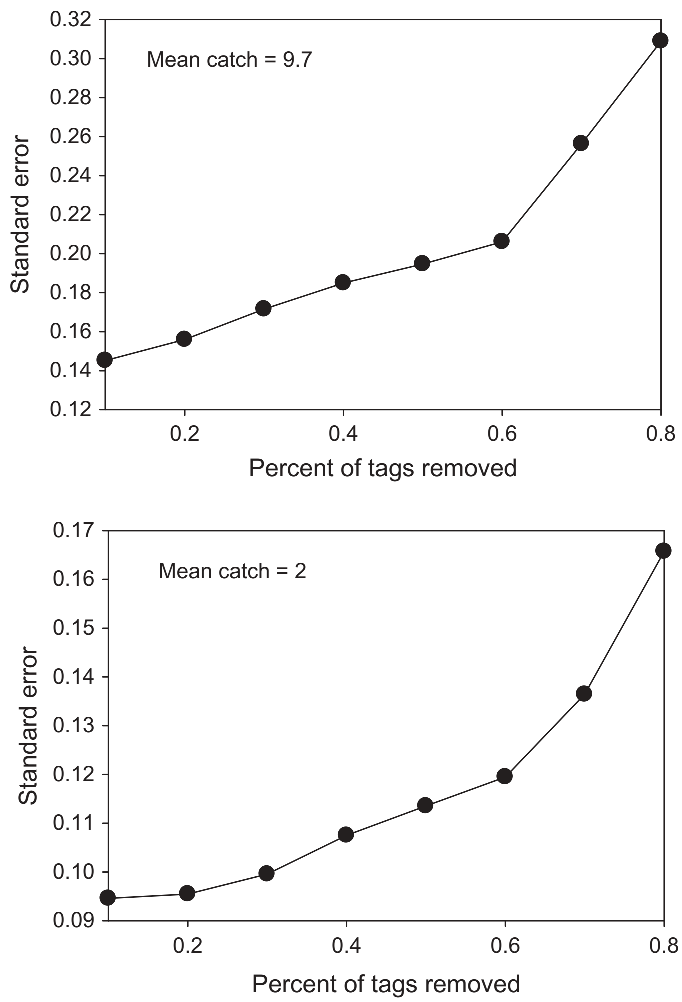

FIGURE 2. Standard error of simulated mean catch estimates when 10–80% of tags were removed from fish that were caught and released. The top panel represents a scenario where fish were caught 9.7 times on average, and the bottom panel represents a scenario where fish were caught two times on average.

DISCUSSION

Results of the simulation suggest that unbiased estimates of mean catch can be obtained using the models described above when using tag-return studies in fisheries with high rates of catch and release when tags may be removed or left intact. However, there were several assumptions when using model-derived estimates of mean catch, including the assumption that all tags were reported. Although this assumption is seldom met in practice, when the reporting rate is known or estimated from an independent study or with high-reward tags (e.g. Pollock et al. 1991; Meyer et al. 2012), mean catch can be divided by the reporting rate to provide an unbiased estimate of mean catch. However, even with known reporting rates, the assumption that all tags that are removed from released fish are reported must be met to provide unbiased estimates of mean catch using this model. If this assumption is not met, mean catch will be underestimated. Additional assumptions common to all tag-return studies (e.g., no tag loss, independence among tags) must also be met using the methods described in this study (Pollock et al. 1991).

Not surprisingly, estimates of mean catch were negatively biased when naïve observed tag returns were used to represent mean catch. Additionally, estimates were biased when using only observations of tags left intact when catch rates were low (i.e., when catch data were generated using the negative binomial distribution). Estimates were unbiased when mean catch was relatively high. When mean catch was high, nearly every fish was caught at least once. Thus, the distribution of catch was similar for fish that were caught and released with tags removed and fish that were caught and released with tags intact, and unbiased estimates resulted. However, when mean catch was relatively low, there were many fish that were never caught. Because a fish has to be caught at least once for the tag to be removed, the data set using only observations of fish with tags left intact had a much higher proportion of zeroes than the actual catch data. Therefore, estimates were biased low and bias increased as the proportion of fish that were released with tags removed increased.

The standard error of model-derived estimates increased as the number of tags that were removed from fish that were released increased. In practice, it may be possible to increase the frequency of anglers releasing fish with tags intact with a publicity campaign (Conroy and Williams 1981; Pollock et al. 1991) that encourages anglers to not remove tags from fish they plan to release. Driscoll et al. (2007) released tags with "Do Not Remove" printed on them in a study to evaluate the impacts of tournament angling on populations of Largemouth Bass *Micropterus salmoides* in Texas. Estimates of mean catch will remain unbiased if no tags are removed using the methods described in this study, as the likelihood reduces to the standard uncensored likelihood under such scenarios. However, it is unlikely that all anglers will be aware that tags should not be removed and some level of censoring may still occur. Furthermore, actions such as publicity campaigns or releasing tags with "Do Not Remove" printed on them may affect reporting rates.

Distributions of empirical fish catch data will need to be assessed using common model diagnostics (Fox 2008). The Poisson distribution is commonly used to model count data because the specified variance is equal to the mean (Rice 2007), a phenomenon that is often observed with count data. In contrast, the negative binomial distribution has an additional parameter that allows for overdispersed data where the variance differs from the mean and is frequently used to model fisheries catch data (Moyle and Lound 1960; Brodziak and Walsh 2013; Irwin et al. 2013). Additionally, multiple distributions can be fit to the same data, and information theory can be used to select among candidate models or to create model-averaged parameter estimates (Akaike 1973; Smith et al. 2000; Burnham and Anderson 2002).

The methods described in this study to estimate mean catch can be used when fish are harvested or released. However, estimating the two components of catch separately is not possible using the current form of the model and other methods may be necessary if true angling exploitation rate is of interest. On-site creel surveys (Pollock et al. 1994) have traditionally been used to estimate catch in fisheries with high rates of catch and release. Tag-return models can often provide a cost-effective alternative to on-site creel surveys and estimates of catch may be more precise (Pollock et al. 1991; Meyer and Schill 2014). The models presented here provide a relatively simple method for estimating mean catch using tag-return studies in such fisheries. Although statistical models to handle censored data are well developed, more work is needed to evaluate how possible violation of the assumptions of the models presented here can affect catch estimates.

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