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Tag Reporting Rate Estimation: 1. An Evaluation of the High-Reward Tagging Method

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Abstract.—Tag-return models can be used to estimate survival rates and tag recovery rates. The additional knowledge of an estimated tag reporting rate allows one to separate total mortality into fishing and natural mortality rates. This paper examines the use of high-reward tags in tagging studies. We find that many of the problems encountered in tagging studies can be avoided if tagged animals are released in small batches in as many locations as possible rather than in large batches at a few locations. Often, the use of substantial monetary rewards for the return of standard tags may be justified as cost effective because of the higher tag return rates they induce. The high-reward tagging method is an important method for estimating the tag reporting rate for standard tags. For this method it is assumed that high-reward tags are reported 100% of the time. This assumption is investigated. Other assumptions of the method are also considered, and particular attention is paid to whether the reporting rate of standard tags may change when a high-reward tagging study is initiated. This is of particular concern in cases in which standard tags are used for all study years and high-reward tags are only used in some subset of the study years. If the natural mortality rate is assumed to be constant over all years, then fishing and natural mortality together with two tag reporting rates can be estimated. Simulation analysis shows that fishing mortality estimates are unbiased in this case but have significantly higher coefficients of variation in the years without high-reward tags. Natural mortality estimates are unbiased and reasonably efficient, but this is crucially dependent on the assumption that natural mortality is constant over time. We make detailed recommendations for improving the design of reward tagging studies in general.

The Brownie models (Brownie et al. 1985) are now the standard method of analyzing wildlife tag-return data. They also have provided a sound basis on which to build many new developments in the analysis of fishery tag-return data (e.g., Pollock et al. 1991; Hearn et al. 1998; Hoenig et al. 1998a, 1998b). Here we present a review of how tag rewards affect the results of, and conclusions from, a multiyear tagging program. We evaluate how information on the tag-reporting rate of standard tags can be obtained by high-reward tagging programs and how the information can be used in conjunction with a Brownie tagging model to partition total mortality into fishing and natural mortality components.

The basic logic behind the use of multiyear tagging studies to estimate total mortality is as follows: two cohorts of tagged fish are released 1 year apart; the fraction of the tags recovered in any subsequent year would be the same for the two cohorts except that one cohort has been at liberty an extra year and thus had its numbers decreased by an additional year of mortality. This difference in tag-return rates allows for estimation of total

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mortality. The exploitation rate (a function of fishing and natural mortality) can also be estimated as follows: the fraction of tags recovered in a year is equal to the number of tags present at the start of the year times the exploitation rate times the tag-reporting rate. Hence, if the tag-reporting rate can be estimated, the exploitation rate can also. For example, if high rewards are offered for the return of tags so that the tag-reporting rate is 100%, then the exploitation rate can be estimated.

Several assumptions are inherent in all of these multiyear tagging models. (1)The tagged sample is representative of the target population, (2) there is no tag loss, (3) survival rates are not affected by tagging, (4) the year of tag recoveries is correctly reported, (5) the fate of each tagged fish is independent, and (6) all tagged fish within a cohort have the same annual survival and recovery rates.

Assumption (1) implies that the tagged animals are well mixed with the animals without tags. This can be ensured by tagging animals at numerous locations dispersed throughout the stock area. A test of the assumption of mixing can be made by comparing the fit of a model that assumes a well-mixed situation with that of a model that allows for nonmixing of newly tagged animals (Hoenig et al. 1998b). Alternatively, the spatial distribution of newly tagged animals can be compared with that of previously tagged animals by the use of, for example, a χ^2 test (Latour et al. 2001a). Hoenig et al. (1998b) found that a modest amount of nonmixing could cause a substantial bias in mortality estimates.

The assumption of no tag loss (2) can be violated in two ways: via tag loss in the first few days after tagging and via ''chronic'' tag loss that is spread out over an extended period of time. The former type of tag loss is inconsequential for the classic Brownie model in which survival (and tag recovery rate) parameters are estimated *provided* that the initial tag loss is constant from year to year. This type of tag loss must be accounted for when components of mortality are estimated. Chronic tag loss affects all types of tag analysis and is difficult to deal with. If double-tagging experiments, in which some fish get two tags, are conducted to quantify chronic tag loss, it may be possible to inflate tag recovery numbers to account for tag loss.

If survival of fish is influenced by tagging (assumption [3]), then survival estimates will not apply to untagged animals. Sometimes fish are held in enclosures to evaluate short-term holding mortality (e.g., Beverton and Bedford 1963; Latour et al. 2001b).

Sometimes the year of recovery is not correctly recorded (assumption [4]); the departure is to report in a later year than the actual harvest date. This will cause a positive bias in survival estimates and a negative bias in total mortality. (It is not known how this incorrect recording affects estimates of fishing and natural mortality, and detailed simulations would need to be done to establish the effect under different scenarios.)

The assumption of the independence of tagged fish (5) is likely violated in all real studies. This will not usually cause model bias in the estimates of survival rate, but it will mean that sampling variances are larger than those reported. Therefore calculated confidence intervals will be narrower than they should be (Pollock et al. 1991). However, when high-reward tags are used, the lack of independence can cause changes in fisher behavior and thus bias in estimates of fishing and natural mortality rates. We return to this important point in the discussion.

The assumption of homogeneity of survival and recovery rates (6) has been studied by Pollock and Ravelling (1982) and Nichols et al. (1982) in a wildlife tagging context. The induced bias in estimates of survival will not be substantial in most cases unless there is a correlation between true survival and recovery rate distributions. The effects of failures of this assumption on estimates of fishing and natural mortality rates have not been studied.

Following the notation of Brownie et al. (1985), the general form for representing tag-return data is an upper triangular data matrix of recoveries (R_{ij}). There are I yearly cohorts of tagged animals, and there are J years of recovery data; N_i is the cohort size for year i; and R_{ij} is the number of tag recoveries in year j from those originally tagged in year i. Only the first cohort can be followed for all J years. The next cohort can be followed for $J - 1$ years, and the last cohort is only followed for $J - (I - 1)$ years. Tagging periods do not have to be yearly intervals. However, analysis is easiest if periods are the same length and all tagging events are done at the beginning of the interval. The expected recovery rates (for the Brownie model that allows year-specific survival and recovery rates) can be displayed in a similar matrix. The expected value for cell R_{11} is $N_1 f_1$, for R_{12} is $N_1 S_1 f_2$, for R_{13} is $N_1 S_1 S_2 f_3$, and so on. Here f_i is the tag recovery rate in year i, and S_i is the survival rate over year i. Data entries for each row have a multinomial distribution. We do not present it here, but the overall likelihood for the model is simply the product of the individual row likelihoods because the rows (cohorts) are independent (Brownie et al. 1985; Hoenig et al. 1998a). Solving for maximum likelihood estimates of the parameters is a simple but iterative process, and several software packages have been designed specifically for analyzing tag-return data. These programs include SURVIV (White 1983), MARK (see http://cnr.colostate.edu/FWB), and AVOCADO (Hoenig et al. unpublished manuscript; available from authors).

The Brownie model, as presented above, can be used to estimate survival rates S and tag recovery rates f, but with additional information the components of the mortality can also be estimated. Note that the tag recovery rate is the product of two parts, $f = \lambda u$, where u is the exploitation rate and λ is the probability that a tag on a harvested fish is reported. So if λ can be estimated, then so can u. Pollock et al. (1991) and then subsequent authors (Hoenig et al. 1998a, 1998b) found it convenient to express the Brownie models in terms of the instantaneous rates of fishing (F) and natural mortality (M). The survival rate is always of the form $S = \exp(-F - M)$, whereas the form of the exploitation rate u depends on the timing of the fishery. This approach requires the following additional important assumption: (7) fishing and natural mortality processes are additive.

This assumption is standard in fisheries modeling. It has been investigated in wildlife tagging studies in which there is the suspicion of compensatory mechanisms operating (see for example Burnham and Anderson 1984). The evidence for lack of additivity is mixed, and we believe that in most fisheries the assumption is justified.

The structure of the paper is as follows: we review how high-reward tagging can be used to estimate reporting rate, and then we consider the costs of high-reward tagging programs. Next we present the results of a small simulation study to assess changes in the reporting rate of standard tags when high-reward tags are present. We end the paper with a discussion of design improvements for high-reward tagging studies.

High-Reward Tagging to Estimate the Reporting Rate

Several methods have been used to estimate the tag reporting rate. It is theoretically possible to estimate the reporting rate from tagging data alone if natural mortality is assumed to be constant over time (Youngs 1974; Siddeek 1989, 1991; Hoenig et al. 1998a). However, except in special situations, the estimates are extremely imprecise. An improvement is to use a special design and model involving two tagging events per year (Hearn et al. 1998). Another method is called the planted tags method. A known number of tags is surreptitiously planted by fishery agents into the catch of private fishers or into the catch of a commercial fishery. Then the tag-reporting rate can be estimated by dividing the number of planted tags reported by the known number of planted tags (Costello and Allen 1968; Green et al. 1983). Planted tags are difficult to use in recreational fisheries because of the need for secrecy but may be feasible in commercial fisheries with large catches. Angler or port surveys can also be used to estimate reporting rates (Pollock et al. 1991). This method involves having a survey agent monitor all catches for some probability sample of fish ports in a commercial fishery or access points in a recreational fishery. Thus it is possible to estimate how many tags were harvested, and one already knows how many harvested tags were reported. The reporting rate estimate is simply the ratio of these two quantities. Another method involves the use of catch from a multicomponent fishery in which one component has a reporting rate of 100% (an example would be a boat fishery with and without observers) (Paulik 1961; Kimura 1976; Hearn et al. 1999; Pollock et al. 2001).

Here, we focus on the use of high-reward tagging that is probably the most common method used in practice. If two types of tags are used (standard tags and high-reward tags), then the tag-reporting rate can be estimated as long as the reward level is high enough that there is a 100% return rate for high-reward tags. The standard tag-reporting rate can then be estimated as the relative recovery rate of standard tags to the recovery rate of high-reward tags (Henny and Burnham 1976; Conroy and Blandin 1984; Pollock et al. 1991). This is given by the following formula, if we only consider recoveries in the first year:

$$\hat{\lambda} = R_s N_r / (R_r N_s) \tag{1}$$

where R_s is the number of standard tags returned, N_s is the number of standard tags released, R_r is the number of high-reward tags returned, and N_r is the number of high-reward tags released. It is possible to use all recoveries in all years in a general multinomial model (Conroy 1985; Hoenig et al. 1998a).

Rewards must be high enough that all high-reward tags are reported. If this assumption is violated, then the estimate of the standard tag-reporting rate will be positively biased. Nichols et al. (1991) used a variety of different reward levels in a special study on mallard ducks *Anas platyrhynchos platyrhynchos.* They found that a reward of US$100 (in 1988 dollars) appeared necessary to reach 100% reporting of the high-reward tags. The level of reward necessary is likely to vary among species, locations, and group affiliation of the fishers. There may also be some ''hardcore'' fishers who refuse to report high-reward tags at any reasonable high-reward level because they are rich, fishing illegally, etc. We also note that the level of reward should be adjusted for inflation in long studies. Murphy and Taylor (1991) also studied variable rewards, but their results were inconclusive because of small sample sizes of the high-reward tags released.

Conroy and Williams (1981) studied the error that arises when equation (1) is used to estimate the standard tag-reporting rate and the reporting rate for high-reward tags is wrongly assumed to be 100%. For the simple case in equation (1), the percent error is $100 \cdot [(1/\lambda_r) - 1)$, where λ_r is the actual reporting rate for the high-reward tags. When the true reporting rate for high-reward tags is above 90%, the error in the estimate for standard tags is less than 11.11% (Figure 1).

It is important to note that fisher behavior may change as a result of implementing a high-reward tagging program. One example could be that some fishers who are aware of the reward program, but not its details, might start reporting standard tags at higher rates than normal, thinking that the standard tags are actually high-reward tags. Alternately some fishers aware of the details might decide not to report the standard tags at all. Another possibility is that the reporting of standard tags may not be independent of the reporting of high-reward tags. For example, a fisher with two or three standard tags may not bother to return them, but if the fisher also catches a fish with a high-reward tag, he or she may return all of the tags. We consider this further in the discussion at the end of the paper.

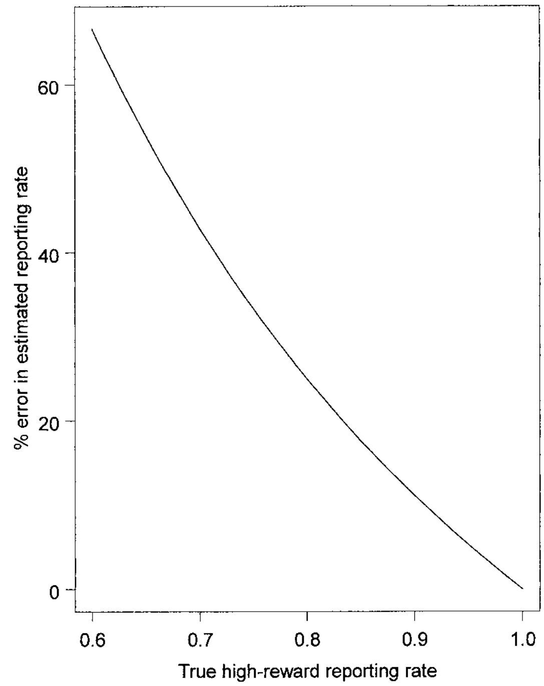

FIGURE 1.—Percentage error in the estimated tag reporting rate for standard tags as a function of the true reporting rate for high-reward tags.

Costs of Standard and High-Reward Tagging Programs

It is often assumed, without evidence, that high-reward tagging programs are too expensive. However, if the tag reporting rate for standard tags is low, it may, in fact, be better to use high-reward tags to get more tag returns for a fixed cost (or to have a lower cost for a fixed number of tag returns). Suppose the goal of a tagging program is to estimate total annual mortality rate (Z), and the task is to determine which type of tag (standard or high-reward) will provide more tag returns for a fixed total cost. In this analysis we ignore the considerable additional benefits such as separation of sources of mortality that accrue from a high-reward tagging study. We assume that the total cost of the tagging study can be approximated by

$$C_f + (N_s + N_r)c_1 + (n_s + n_h)c_2 + n_h R,$$

where C_f is the fixed cost associated with the program, N_s and N_r are the number of standard and high-reward tags released, respectively, c_1 is the cost of tagging a fish (assumed to be the same for the two tag types), n_s and n_h are the number of returns of standard and high-reward tags, respectively, c_2 is the cost associated with processing a tag return and paying a standard reward, and R is the additional cost of a high reward ($R = R_h - R_s$, where R_h and R_s are the values of the high and standard rewards, respectively). We assume that $n_s = N_s u^* \lambda_s$ and $n_h = N_h u^*$, where u^* is the cumulative exploitation rate over the course of the study (fraction of the tagged fish captured by the fishery)

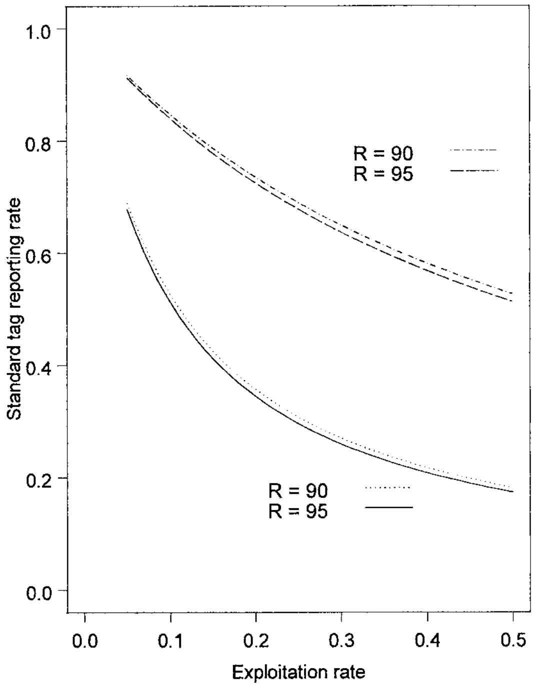

FIGURE 2.—Plot of boundary-showing conditions for which using just high-reward tags provides more tag returns than using just standard tags. For the area below the hyperbola, high-reward tags provide more tag recaptures than standard tags. The difference in rewards between high-reward and standard tags equals US$95 (R = 95) or $90 (R = 90). The cost of tagging and releasing a fish equals $10 (lower pair of curves) and $50 (upper pair of curves)

and λ_s is the tag-reporting rate for standard tags. (It is assumed that all high-reward tags are reported.) Under these conditions it can be shown (Appendix 1) that more tags will be recovered when high-reward tags are used instead of standard tags when

$$R < \frac{c_1\left(\frac{1}{\lambda_s} - 1\right)}{u^*}.$$

Suppose the rewards associated with standard and high-reward tags are $5.00 and $100.00, respectively ($R$ = $95.00) and the marginal cost c_1 associated with tagging a fish is $10.00. Then for any specified values of u^* and λ_s, we can determine which tag type will provide more returns (Figure 2). For the standard tag to provide more tag returns than does the high-reward tag, the combination of λ_s and u^* must be above the hyperbolic line in Figure 2. If we double the standard tag reward from $5.00 to $10.00, the hyperbolic line moves slightly upward. If the exploitation rate is very low, then the tag-reporting rate for standard tags would have to be high for standard tags to provide more tag returns than high-reward tags provide. If the marginal cost of tagging a fish is $50.00 instead of $10.00, the picture changes considerably (Figure 2). Now, for standard tags to provide more tag returns, the reporting rate for standard tags would have to be high even for high exploitation rates. In a variable-reward tagging study of banded birds, Nichols et al. (1991, their Figure 1) found that the reporting rate for standard tags with a $5.00 reward was about 42% whereas the reporting rate for $10.00 tags was about 50%. If these values were realistic for the tagging study considered here, a $10.00 reward would not be sufficient to provide more tag returns than a high-reward tagging program of equal expected cost for exploitation rates up to 50%.

Our point is that high-reward tagging studies should not be dismissed out of hand as being too expensive. We can construct realistic scenarios in which a high-reward tagging program can provide better estimates of the total mortality rate than a tagging program that employs low-reward standard tags. Because high-reward tags also offer the potential to estimate fishing and natural mortality rates, it is worth considering carefully the benefits and costs associated with high-reward tags.

Assessment of Changes in Reporting Rate Due to High Rewards

Simulation methods.—We examined a model in which there are 6 years of tagging data but high-reward tags are only used during the last 3 years of the study. This model uses an instantaneous rates formulation (Ricker 1975; Hoenig et al. 1998a) and assumes a type I (pulse) fishery. With instantaneous rates, the formulae for S_i and u_i are expressed in terms of the instantaneous rates of fishing and natural mortality. Recall, for year i, that S_i is the annual survival rate, u_i is the annual exploitation rate, F_i is the instantaneous rate of fishing mortality, and M is the instantaneous rate of natural mortality [$S_i = \exp(-M - F_i)$; $u_i = 1 - \exp(-F_i)$].

The recovery probability structure for this model is shown in Table 1. We specify a 100% reporting rate for high-reward tags. We allow the standard tag reporting rate to be different for the 3 years during which there are no high-reward tags than for the 3 years during which high-reward tagging is also done. This might happen in practice,

TABLE 1.—Recovery probabilities for high-reward and standard tags in a partial-reward tagging study. Note that $S_i = \exp(-F_i - M)$ = annual survival rate in year i; $u_i = 1 - \exp(-F_i)$ = annual exploitation rate in year i; F_i is the instantaneous rate of fishing mortality in year i; M is the instantaneous rate of natural mortality, specified to be constant over all years; N_{is} is the number of standard tags released in year i; N_{rs} is the number of high-reward tags released in year i; λ_1 is the reporting rate of standard tags when no high-reward tagging is occurring; and λ_2 is the reporting rate of standard tags when high-reward tagging is occurring.

Year of tagging	Number tagged	Probability of recovery					
		1	2	3	4	5	6
1	N_{1s}	$u_1\lambda_1$	$S_1u_2\lambda_1$	$S_1S_2u_3\lambda_1$	$S_1S_2S_3u_4\lambda_2$	$S_1S_2S_3S_4u_5\lambda_2$	$S_1S_2S_3S_4S_5u_6\lambda_2$
2	N_{2s}		$u_2\lambda_1$	$S_2u_3\lambda_1$	$S_2S_3u_4\lambda_2$	$S_2S_3S_4u_5\lambda_2$	$S_2S_3S_4S_5u_6\lambda_2$
3	N_{3s}			$u_3\lambda_1$	$S_3u_4\lambda_2$	$S_3S_4u_5\lambda_2$	$S_3S_4S_5u_6\lambda_2$
4	N_{4r}				u_4	S_4u_5	$S_4S_5u_6$
4	N_{4s}				$u_4\lambda_2$	$S_4u_5\lambda_2$	$S_4S_5u_6\lambda_2$
5	N_{5r}					u_5	S_5u_6
5	N_{5s}					$u_5\lambda_2$	$S_5u_6\lambda_2$
6	N_{6r}						u_6
6	N_{6s}						$u_6\lambda_2$

due to a high-reward tagging study starting well after standard tagging has begun, and thus cause a change in fisher behavior in response to the high-reward tags being present. We suspect that this may have happened in a recent tagging study of red drum *Sciaenops ocellatus* (Latour et al. 2001b). Thus λ_1 is the standard tag-reporting rate during the 3 years in which there are no high-reward tags, and λ_2 is the standard tag-reporting rate during the high-reward tag period. We also specify the natural mortality rate (M) to be constant over all 6 years.

The program SURVIV (White 1983) is a well-documented and widely used program designed to give maximum likelihood estimates of the parameters that make up the cell probabilities in tagging models. This software is flexible in that it allows the user to provide constraints for individual parameters. The program can be used for any situation in which we have a product multinomial likelihood. It has been tested and revised over many years and uses a numerical search algorithm to find the maximum. The program can be used to analyze data and to perform simulations. We used the simulation option in SURVIV to test whether this model could, in fact, provide unbiased and efficient estimates of the natural mortality rate, the tag reporting rates, and the fishing mortality rates for all years, even those when there was no high-reward tagging. For these simulations we varied the fishing mortality rates, standard tag reporting rates, natural mortality rates, and numbers tagged. High-reward tag-reporting rates were always set at 1.0, and the solutions were constrained to always estimate this parameter as 1.0. All results are based on means and SEs of parameter estimates for the 1,000 simulation repetitions.

Simulation results.—The simulation results for the scenarios in which the standard tag cohort is 1,000 tags per year, the high-reward tag cohort is 200 tags per year, and the natural mortality rate is 0.2 can be seen in Table 2. The only parameter estimate that is biased is the tag reporting rate in the years in which there were no high-reward tags. The biases are greatest when the tag reporting rates are low ($\lambda_1 = 0.3$ and $\lambda_2 = 0.4$; bias = 14%) and decrease as the tag reporting rates are higher ($\lambda_1 = 0.6$ and $\lambda_2 = 0.7$; bias = 6%). These biases decrease by about one-half when the year 1–3 and the year 4–6 fishing mortality rates are increased from 0.2 and 0.3 up to 0.3 and 0.4, respectively. Fishing mortality estimates are much less precise in the years in which there are no high-reward tags. The year 1–3 fishing mortalities tend to have coefficients of variation that are three to four times as large as those in years 4–6. Notice that increasing the fishing mortality rates or the tag-return rates decreases coefficients of variation because both changes result in more tags being recovered.

The coefficients of variation (= 100•SE/mean) for the natural mortality estimates are in the range of 18–26%. We believe that this is quite acceptable considering the difficulties in estimating the natural mortality rate by other methods.

The natural mortality rate is increased from 0.2 to 0.4 (Table 3). In all scenarios the higher level of natural mortality leads to a larger bias in the year 1–3 tag reporting rate and larger coefficients of variation in the tag-reporting and fishing mortality parameters. However, the coefficients of variation for M are substantially reduced (range, 11–15%).

Table 4 shows what happens if the tagging effort is increased by releasing high-reward tags in all 6 years. The results for just one combination of ex-

TABLE 2.—Partial reward tag simulation results for a 6-year study in which the instantaneous natural mortality rate = 0.2, the standard tag cohort size = 1,000, and the high-reward tag cohort size = 200. The coefficient of variation is defined as 100·SE/mean. The scenario designations are based on (1) the instantaneous rates of fishing mortality (F) and (2) the reporting rates over successive 3-year intervals; for example, 23_34 indicates that F is 0.2 for 3 years and 0.3 for the next 3 years and that the reporting rate is 0.3 for 3 years and 0.4 for the next 3 years.

Scenario	Parameter	Actual value	Parameter estimate	SE	Coefficient of variation	Proportional bias
23_34	F_1	0.2	0.199	0.070	0.35	−0.005
	F_2	0.2	0.200	0.069	0.35	0.001
	F_3	0.2	0.200	0.071	0.36	−0.002
	F_4	0.3	0.297	0.023	0.08	−0.010
	F_5	0.3	0.297	0.023	0.08	−0.009
	F_6	0.3	0.297	0.028	0.09	−0.012
	λ_1	0.3	0.342	0.145	0.42	0.140
	λ_2	0.4	0.404	0.025	0.06	0.011
	M	0.2	0.200	0.051	0.26	0.002
23_67	F_1	0.2	0.199	0.050	0.25	−0.003
	F_2	0.2	0.200	0.050	0.25	0.000
	F_3	0.2	0.200	0.050	0.25	0.000
	F_4	0.3	0.297	0.020	0.07	−0.010
	F_5	0.3	0.297	0.020	0.07	−0.010
	F_6	0.3	0.297	0.024	0.08	−0.010
	λ_1	0.6	0.634	0.147	0.23	0.057
	λ_2	0.7	0.707	0.039	0.06	0.010
	M	0.2	0.201	0.038	0.19	0.005
34_34	F_1	0.3	0.298	0.071	0.24	−0.007
	F_2	0.3	0.297	0.067	0.23	−0.009
	F_3	0.3	0.298	0.070	0.23	−0.006
	F_4	0.4	0.396	0.027	0.07	−0.011
	F_5	0.4	0.397	0.027	0.07	−0.007
	F_6	0.4	0.395	0.033	0.08	−0.012
	λ_1	0.3	0.316	0.068	0.22	0.053
	λ_2	0.4	0.404	0.022	0.05	0.009
	M	0.2	0.203	0.048	0.24	0.016
34_67	F_1	0.3	0.298	0.050	0.17	−0.006
	F_2	0.3	0.298	0.049	0.16	−0.006
	F_3	0.3	0.298	0.050	0.17	−0.006
	F_4	0.4	0.397	0.024	0.06	−0.007
	F_5	0.4	0.396	0.023	0.06	−0.010
	F_6	0.4	0.396	0.028	0.07	−0.009
	λ_1	0.6	0.616	0.084	0.14	0.026
	λ_2	0.7	0.706	0.032	0.05	0.009
	M	0.2	0.203	0.036	0.18	0.014

ploitation rates and mortality rate are presented. This can be compared with the first scenario in Table 2. The coefficients of variation are clearly much smaller in the model with 6 years of high-reward tagging, being one-half to one-third of the size of the model results with just 3 years of high-reward tagging. In addition, if high-reward tagging is done every year, then it is not necessary to assume that natural mortality is constant although we make this assumption in these simulations.

Conclusions and Design Implications

High-reward tagging is one fairly common method used to estimate the tag reporting rate. For validity, it is essential that a large enough reward be used to ensure that 100% of the high-reward tags are reported. In addition, a publicity campaign must be conducted so that fishers know to look for high-reward tags; otherwise they may ignore them. Conroy and Williams (1981) show that a serious bias occurs in standard tag-reporting rate estimates if the assumption of complete reporting of high-reward tags is violated (see Figure 1). This will lead to a negative bias in estimates of F and a positive bias in M.

It is worth noting how tagging studies can go awry. One way is for tag returns to not be independent. The problem can be inferred to exist when fishers return batches of tags. For example, a fisher may hold onto two or three tags, each of which is worth a $5.00 reward. But if the fisher catches a fourth tagged fish, there may be enough cumulative incentive to return the four tags. This problem will be minimized if tagging is conducted at a large

TABLE 3.—Partial reward tag simulation results in which the instantaneous natural mortality rate = 0.4, the standard tag cohort size = 1,000, and the high-reward tag cohort size = 200. See the caption to Table 2 for explanation of scenario designations.

Scenario	Parameter	Actual value	Model estimate	SE	Coefficient of variation	Proportion bias
23_34	F_1	0.2	0.200	0.080	0.40	0.002
	F_2	0.2	0.201	0.078	0.39	0.006
	F_3	0.2	0.202	0.082	0.40	0.010
	F_4	0.3	0.297	0.025	0.08	−0.010
	F_5	0.3	0.298	0.024	0.08	−0.007
	F_6	0.3	0.297	0.028	0.10	−0.011
	λ_1	0.3	0.356	0.180	0.50	0.188
	λ_2	0.4	0.404	0.028	0.07	0.010
	M	0.4	0.401	0.058	0.15	0.001
23_67	F_1	0.2	0.202	0.057	0.28	0.009
	F_2	0.2	0.202	0.056	0.28	0.012
	F_3	0.2	0.203	0.058	0.29	0.013
	F_4	0.3	0.298	0.021	0.07	−0.008
	F_5	0.3	0.297	0.022	0.07	−0.010
	F_6	0.3	0.297	0.025	0.09	−0.010
	λ_1	0.6	0.638	0.166	0.26	0.063
	λ_2	0.7	0.707	0.042	0.06	0.010
	M	0.4	0.400	0.043	0.11	0.000
34_34	F_1	0.3	0.297	0.081	0.27	−0.010
	F_2	0.3	0.296	0.079	0.27	−0.012
	F_3	0.3	0.297	0.082	0.28	−0.009
	F_4	0.4	0.396	0.029	0.07	−0.010
	F_5	0.4	0.397	0.029	0.07	−0.007
	F_6	0.4	0.395	0.034	0.09	−0.011
	λ_1	0.3	0.324	0.094	0.29	−0.081
	λ_2	0.4	0.404	0.023	0.06	0.009
	M	0.4	0.404	0.057	0.14	0.009
34_67	F_1	0.3	0.298	0.060	0.20	−0.006
	F_2	0.3	0.298	0.059	0.20	−0.006
	F_3	0.3	0.298	0.059	0.20	−0.008
	F_4	0.4	0.397	0.026	0.07	−0.009
	F_5	0.4	0.397	0.026	0.06	−0.008
	F_6	0.4	0.396	0.030	0.08	−0.010
	λ_1	0.6	0.623	0.108	0.17	0.038
	λ_1	0.7	0.707	0.036	0.05	0.010
	M	0.4	0.403	0.044	0.11	0.007

number of locations dispersed throughout the stock area so that a fisher is not likely to encounter many tags. Another way to avoid the problem is to increase the tag reward so that it becomes worthwhile to return even a single tag. Also tags may not be independent when a novelty is offered instead of a cash reward. Fishers may tire of novelties (how many hats does a fisher need?). Hence, the first tagged fish caught may be reported with higher probability than the later-caught fish if only

TABLE 4.—High-reward tag simulation results with high-reward tags in all 6 years; the instantaneous natural mortality rate = 0.2, the standard tag cohort size = 1,000, and the high-reward tag cohort size = 200. See the caption to Table 2 for explanation of the scenario designation.

Scenario	Parameter	Actual value	Model estimate	SE	Coefficient of variation	Proportional bias
23_34	F_1	0.2	0.197	0.023	0.12	−0.015
	F_2	0.2	0.198	0.019	0.10	−0.010
	F_3	0.2	0.198	0.018	0.09	−0.010
	F_4	0.3	0.297	0.019	0.06	−0.009
	F_5	0.3	0.298	0.020	0.07	−0.008
	F_6	0.3	0.297	0.023	0.08	−0.010
	λ_1	0.3	0.304	0.025	0.08	0.012
	λ_2	0.4	0.404	0.020	0.05	0.010
	M	0.2	0.203	0.019	0.10	0.014

novelties are offered. Again, this problem is minimized if a fisher is not likely to encounter many tagged fish because tagging is spread out. It is also possible to avoid satiation by offering a variety of rewards (hats, t-shirts, mugs, and tote bags, in designs that change from year to year) with a cash reward option equivalent in value to the novelties (Pollock et al. 2001). A third example of lack of independence is when a fisher catches a fish with a standard tag and retains it without reporting it; if this fisher then catches a high-reward tag, the fisher may send in both tags. This will cause the reporting rate for standard tags to be overestimated. Investigators should proceed with caution when standard tags are commonly reported together with a high-reward tag. Dispersal of tagging effort over space will minimize the problem.

We find that biologists are hesitant to implement high-reward tagging programs for fear of an unexpectedly high return of high-reward tags bankrupting the program. There are two cases to consider. First, if high-reward tags are released at just a few locations, it is possible for fishers to return an especially high (or low) proportion of tags depending on whether fishing effort is high in tagging areas. Fishers may even ''fish for tags'' if it is profitable. The best solution is to disperse the tags throughout the stock area. Second, an unexpectedly high proportion of high-reward tags may be recovered because the exploitation rate is much higher than believed. In this case, the stock assessment is simply wrong, and the extra cost of the tagging program is likely a great bargain considering the importance of the information gained.

An important question needing more study is how to design a multiyear tagging study optimally for estimating fishing and natural mortality rates. The problem has several dimensions. First, there is the question of how to allocate resources to standard and high-reward tags. But, there is also the question of how to allocate the number of standard and high-reward tags to the years of tagging. It may be that greater efficiency is achieved when more effort is put into releasing tags in the earlier years of the study than in the later years. (This contradicts somewhat the common idea of starting with a pilot study to determine allocation strategies and then increasing the tagging effort appropriately.) It is important to note that the standard tags serve to place a constraint on the sum (Z) of the fishing and natural mortality rates; the high-reward tags serve to divide the total mortality rate into its components. Thus, there is a limit to what the standard tags can accomplish in terms of reducing the variance of estimates of fishing and natural mortality.

Often a high-reward tagging study is performed only for a part of the standard tagging study. In this case the typical analysis assumes that we can apply the reporting-rate estimate obtained to the earlier years, before the high-reward study began, as well as to the later years during the high-reward study. We believe that this is a dangerous approach that should be avoided. We recommend that a model be fitted to the data that allows for the reporting rate to change, due to a change in fisher behavior. It is theoretically possible to fit this model with two reporting rates, yearly fishing mortality rates, and a constant natural mortality rate. The key is the assumption of a constant natural mortality rate. Our simulations show that the model can give reasonable estimates for the F_i and M but that the tag reporting rate for the years before the high-reward tagging may have some bias.

Design recommendations are as follows:

1. We believe that, in general, it is a poor idea to conduct a tagging study in which no reward is offered for standard tags. The tag reporting rate is likely to be very low (Youngs 1974; Nichols et al. 1991; Frusher and Hoenig 2001) and is also likely to vary substantially over segments of the fishing population, possibly leading to a bias. If the tagging study is worthwhile, it is worth doing it right. Also, tagging programs that rely on cooperating fishers to release tagged fish are likely to be problematic. If no reward is offered, the tag-reporting rate is likely to be very low, but if a desirable reward, monetary or otherwise, is offered, the possibility arises of fraud occurring associated with tags being given to friends to exchange for rewards without any tagging ever actually taking place.

2. In general, we do not recommend lotteries for a few reasons. They may increase the tag reporting rate but to an unknown degree. They require financial and personnel resources to be run properly. Generally, the prizes are awarded at the end of the season when it is too late to influence fisher behavior, whereas fisher behavior can best be influenced to increase reporting of tags if prizes are awarded throughout the season. The opportunity cost of running a lottery can be substantial. For example, instead of awarding three \$1000.00 prizes, one could tag more than 30 fish with \$100.00 high-reward tags. Biologists who conduct lotteries can create expectations among the fishers in other fisheries. Cooperation may become low in tagging programs without lotteries. A decision to end a lottery may cause a decrease in the reporting rate.

3. Release high-reward tags in the same way as standard tags and spread the tags as evenly as possible over the fishery area. Do not release high-reward tags in large batches in one or two areas because this is likely to lead to extreme nonmixing of the high-reward tags and to cast doubt on the validity and precision of the reporting rate estimates obtained.

4. The presence of high-reward tags in the fishery will likely change fisher behavior with respect to standard tags. Therefore, the high-reward tagging should ideally be run concurrently for all of the years of the standard tagging study. This should promote stability in the standard tag-reporting rate but also allows the reporting rate to be estimated separately every year if necessary.

5. The 100% reporting rate for high-reward tags, which is required for the method to work properly, implies that the reward value is sufficiently high and also that fishers recognize the high-reward tags. The former can be investigated by use of a variety of reward levels (e.g., Murphy and Taylor1991; Nichols et al. 1991). The latter can be ensured by conducting a proper publicity campaign, the effectiveness of which should be investigated by interviewing fishers to determine what proportion of the fishers are aware of the high-reward tagging program. Fishers unaware of the high-reward tagging program may not bother to examine tags to determine their value.

6. It would be helpful if a specific color for high-reward tags could be made standard. Then fishers encountering a high-reward tag from one study would be primed to expect a high-reward tag in other studies in which the standard color is used to denote high rewards.

7. If high-reward tagging does not begin until after the standard tagging study has already started, then fit a model with two different reporting rates, one for each period.

8. It is necessary for the reward level, address, and telephone number to be on the tag in as prominent a manner as possible. Otherwise, there is a chance that a high-reward tag will not be recognized and hence not reported.

9. It should be made easy for fishers to return tags, for example, by placing tag return boxes at access points, supplying prepaid envelopes, and sending personnel to interview fishers.

10. In tagging programs of long duration, consideration of effects of inflation should be taken into account, and reward levels should be adjusted upward on a regular basis every few years.

11. Computer simulations should be used before the fieldwork to evaluate tagging study designs, i.e., the number of standard and high-reward tags released each year. The program SURVIV (White 1983) is useful for this purpose.

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Appendix: Derivation of Conditions under Which High Rewards Produce More Tag Returns than Standard Rewards

Let the total cost of a tagging program be given by

$$\text{total cost} = K = C_f + (N_s + N_r)c_1 + (n_s + n_h)c_2 + n_h R, \quad \text{(A1)}$$

where C_f is the fixed cost associated with the program, N_s and N_r are the number of standard and high-reward tags released, respectively, c_1 is the cost of tagging a fish (assumed to be the same for the two tag types), n_s and n_h are the number of returns of standard and high-reward tags, respectively, c_2 is the cost associated with processing a tag return and paying a standard reward, and R is the additional cost of a high reward ($R = R_h - R_s$, where R_h and R_s are the values of the high and standard rewards, respectively). We assume that $n_s = N_s u^* \lambda_s$ and $n_h = N_h u^*$, where u^* is the cumulative exploitation rate over the course of the study (fraction of the tagged fish captured by the fishery) and λ_s is the tag-reporting rate for standard tags. (It is assumed that all high-reward tags are reported.)

Rearranging equation (A1), we find

$$K = C_f + N_s[c_1 + c_2 u^* \lambda_s] + N_h[c_1 + c_2 u^* + Ru^*], \tag{A2}$$

which can be solved for N_s:

$$N_s = \frac{K - C_f - N_h[c_1 + c_2 u^* + Ru^*]}{c_1 + c_2 u^* \lambda_s}. \tag{A3}$$

If we desire the best estimate of the annual survival rates S, then we want $n_s + n_h$ to be maximized, i.e., to maximize

$$y = N_s u^* \lambda s + N_h u^*.$$

Breaking equation (A3) into parts and substituting into equation (A4) gives

$$y = N_h u^* \left[1 - \frac{(c_1 + c_2 u^* + Ru^*)\lambda_s}{c_1 + c_2 u^* \lambda_s}\right] + \frac{(K - c_f)\lambda_s u^*}{c_1 + c_2 u^* \lambda_s}.$$

This is a linear function of $N_{h.}$ When the slope is negative, the maximum occurs when N_h is zero, implying that the maximum return of tags is obtained when they are all standard tags. The converse is also true. When the slope is zero, the same number of returns will be obtained regardless of whether one uses just high-reward tags or just standard tags. For the slope to be zero,

$$c_1 + c_2 u^* \lambda_s = (c_1 + c_2 u^* + Ru^*)\lambda_s.$$

This is easily solved for R. Thus, more tags will be recovered when high-reward tags are used instead of standard tags when

$$R < \frac{c_1\left(\frac{1}{\lambda_s} - 1\right)}{u^*}$$