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Tag Reporting Rate Estimation: 3. Use of Planted Tags in One Component of a Multiple-Component Fishery

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Abstract.—Tag return models are used to estimate survival and tag recovery rates. With additional information on tag reporting rates, one can separate the survival rate into its fishing and natural mortality rate components. One method of estimating the tag reporting rate is to secretly plant tags in fishers' catches. However, if the fishery has more than one component, it may not be possible to plant tags in all components. Nevertheless, it is possible to estimate the reporting rates of all components in a multiple-component fishery and the fishing and natural mortality rates, if at least one component has a known reporting rate and the catches are known for each component. We simulate a variety of tag return experiments in which tags are planted in one component of a multicomponent fishery. The simulations show that this method is most effective (i.e., provides good precision of parameter estimates) when a sufficient number of tagged fish are planted into a fishery component with a high reporting rate and with a high proportion of the total catch. It is also advantageous to encourage the reporting of tags in the fishery components without planted tags. We provide a method for testing various model assumptions when it is possible to plant tags in more than one component.

The estimation of total mortality rates from multiyear tagging data has a well-developed theory. As described by Brownie et al. (1985), such estimation does not require knowledge of tag reporting rates (i.e., the probability that a fisher who catches a tagged fish will report the tag to the appropriate authorities), nor does it require that tag reporting rates be estimated from the data. However, when information about the tag reporting rate is available in a multiyear study, the mortality from ''natural'' causes and from one or more fisheries can be estimated separately (Pollock et al. 1991; Brooks et al. 1998; Hearn et al. 1998; Hoenig et al. 1998a, 1998b). Also, in a single year, the exploitation rate (the fraction of the stock present at the start of the year that is harvested during the year) can be estimated from tagging data if the tag reporting rate is known.

Two approaches can be used to obtain information about tag reporting rates. The first is to make use of the information about the tag reporting rate that is implicit in the tagging data (Youngs 1974; Siddeek 1989). This internal information comes from the contrast between experiments and is generally quite weak (Hoenig et al. 1998a), but it can be enhanced through special design of the tagging study (see Hearn et al. 1998; Frusher and Hoenig 2001a, 2001b). The second approach is to conduct auxiliary studies to obtain information about reporting rates. These may involve conducting a creel- or port-sampling program (Pollock et al. 1991), releasing special, high-reward tags

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for which the reporting rate can be assumed to be 100% (Henny and Burnham 1976; Nichols et al. 1991; Pollock et al. 2001, 2002b), placing observers on a portion of the boats (Hearn et al. 1999; Pollock et al. 2002a), and planting a known number of tagged fish in the catches and noting the fraction of tags returned by the fishers.

We focus on the use of planted tags to estimate the tag reporting rate. Although there are a number of examples of the use of this approach (shrimp: Costello and Allen 1968; Campbell et al. 1992; menhaden: Ruppert et al. 1984; sport fish: Green et al. 1983; tunas: Hampton 1997), this method has not been critically reviewed from the perspective of the required assumptions and study design. Specifically, it is frequently the case that only a portion of the boats can be studied using planted tags. For example, an investigator may have access to boats from one country's fleet but not those from another country, or the processing procedure for one fleet may be more conducive to the use of planted tags than that of another fleet. We develop a method to estimate the reporting rate for all fishery components provided that (1) the catches are known (or can be estimated) for each component and (2) the reporting rate of at least one component can be estimated by means of planted tags.

The problem of multicomponent fisheries, in which some components offer no opportunity for sampling, is very common. Hearn et al. (1999) and Pollock et al. (2002b) showed that the reporting, fishing mortality, and natural mortality rates can be estimated in a multiple-component fishery in which catch is known by component provided the reporting rate is 100% in one component. They treated boats with observers as the component with all tags reported (which is analogous to the second requirement in previous paragraph). Thus, the use of planted tags in this paper shows the generality of this approach (i.e., it furnishes a case in which the reporting rate of at least one component can be estimated).

We begin by describing a planted-tag study in a general context and the structure of the tagging data that arises from this design. We then discuss the required assumptions and present some simulation results that provide information on experimental design strategies. We show how to deal with the likely nonrandomness in the tag planting procedure as well as how to check some model assumptions when it is possible to plant tags in more than one fishery component. We conclude with advice on the design of planted-tag studies.

Structure of a Tagging Study with Some Planted Tags

As in a Brownie model, fish are tagged with normal tags (i.e., not planted tags) at the start of each year i ($i = 1, \ldots, I$) and recovered during year j ($j = i, \ldots, J$). Suppose that there are K components to a fishery (for example, different fleets in a commercial fishery or a fishery with recreational and commercial components) and, of all the tagged fish captured in year j, the proportion captured by component k is δ_{jk}. The probability that a tagged fish will be reported in year j from fishery component k, given that it has been caught by component k, is λ_{jk}. The expected number of tags reported from component k involving fish that were tagged in year i and recovered in year j is

$$E(R_{ijk}) = \begin{cases} N_i u_j \delta_{jk} \lambda_{jk} \prod_{h=i}^{j-1} S_h, & (j > i) \\ N_i u_j \delta_{jk} \lambda_{jk}, & (i = j) \end{cases}$$

with

$$\sum_{k=1}^{K} \delta_{jk} = 1$$

In the first set of equations, N_i is the number of fish that were tagged and released at the start of year i, S_h is the annual survival rate in year h, u_j is the annual exploitation rate (i.e., the fraction of the survivors that is caught) in year j, and $\Pi_{h=i}^{j-1} S_h$ is the fraction of the N_i tagged fish that survive up to the beginning of year j. The cell probabilities of returned recaptures for a two-component fishery are shown in Table 1 for the case where the λ and δ parameters are held constant over years.

The table is parameterized in terms of exploitation and survival rates (u and S), but in practice we usually want to link these parameters. This can be accomplished by reparameterizing the model in terms of additive instantaneous rates of fishing and natural mortality, F and M. Then, survival rates can be expressed as

$$S = \exp(-F - M).$$

The exploitation rate is also a function of the fishing and natural mortality rates, but its nature depends on the timing of the forces of mortality. If all fishing occurs as a pulse at the start of the year (i.e., during a short period of time, which is a Ricker [1975] type 1 fishery), then the exploitation rate is

$$u = 1 - \exp(-F).$$

TABLE 1.—Cell probabilities for a multiyear tagging study in which N_i tagged fish are released in year i (i = 1, 2, 3) and recaptures are obtained from two fishery components over a 4-year period. In fishery component 1, N_i^p tags are planted in year i; S = the annual survival rate; u = the exploitation rate; λ = the tag reporting rate; and δ = the fraction of the tagged fish caught in a year that were caught by fishery component 1. Note that $S_i = \exp(-F_i - M)$, where F_i is the instantaneous rate of fishing mortality in year i and M is the instantaneous rate of natural mortality, which is specified to be constant over all years. For type 1 (pulse) fisheries (Ricker 1975), the annual exploitation rate in year i is given by $u_i = 1 - \exp(-F_i)$; for type 2 (continuous) fisheries, it is given by $u_i = (F_i)/(F_i + M)(1 - S_i)$.

Year of tagging	Number tagged or planted	Fishery component	Probability of tag recovery in year 1	2	3	4
1	N_1	1	$u_1\lambda_1\delta$	$S_1u_2\lambda_1\delta$	$S_1S_2u_3\lambda_1\delta$	$S_1S_2S_3u_4\lambda_1\delta$
1		2	$u_1\lambda_2(1 - \delta)$	$S_1u_2\lambda_2(1 - \delta)$	$S_1S_2u_3\lambda_2(1 - \delta)$	$S_1S_2S_3u_4\lambda_2(1 - \delta)$
2	N_2	1		$u_2\lambda_1\delta$	$S_2u_3\lambda_1\delta$	$S_2S_3u_4\lambda_1\delta$
2		2		$u_2\lambda_2(1 - \delta)$	$S_2u_3\lambda_2(1 - \delta)$	$S_2S_3u_4\lambda_2(1 - \delta)$
3	N_3	1			$u_3\lambda_1\delta$	$S_3u_4\lambda_1\delta$
3		2			$u_3\lambda_2(1 - \delta)$	$S_3u_4\lambda_2(1 - \delta)$
1	N_1^p	1	λ_1			
2	N_2^p	1		λ_1		
3	N_3^p	1			λ_1	
4	N_4^p	1				λ_1

If the ratio of fishing and natural mortality is constant over the year, which is a Ricker (1975) type 2 fishery, then

$$u = \frac{F}{F + M}[1 - \exp(-F - M)].$$

A formulation allowing for an arbitrary pattern of fishing over the course of the year is given by Hoenig et al. (1998a). This can be generalized to accommodate competing fisheries with different timing throughout the year (Brooks et al. 1998).

We cannot observe the proportion of the tagged fish caught by fishery component k (δ_{jk}), but under the condition of complete mixing (see Assumptions below), we can assume that it is similar to the fraction of the total catch captured by component k, which can be estimated from known catch and effort statistics or survey data. In our analyses and simulations we treat δ_{jk} as a known constant, but we advise how to incorporate catch uncertainty into our method.

We propose that in one or more components of the fishery, tagged fish are planted in catches to determine the fraction of the fish reported in the component(s). In some cases, the planting of tags can be viewed as independent Bernoulli processes. For example, menhaden have been tagged with coded wire tags. In the fish processing plants, the fish are cooked and ground up and the resulting mush passes by powerful magnets that recover the wire tags. Thus, fish can be planted with known tag numbers in the processing stream to measure the probability of tag recovery. In general, however, tagged fish cannot be randomly planted in the catches of all vessels over all years. Rather, reporting studies involve a two-stage or multistage process in which certain vessel trips are selected each year and then tagged fish are randomly planted in the catch within these trips. If we ignore this sampling structure and treat the planted tags as representing random trials from a Bernoulli process, we will tend to overestimate the precision of our estimate of the reporting rate. We will consider this further in the Results and Discussion sections. For the purpose of describing the planted-tag study design, however, we treat the number of the returned planted tags as a binomial random variable with two parameters: N^p, the number of planted fish, and λ, the tag reporting rate. The cell probabilities are shown in Table 1 for the case in which tags are planted in only fishery component 1.

Each batch or cohort of normally tagged fish (corresponding to a row in Table 1) is viewed as a random sample from a multinomial distribution. As in a Brownie model, the likelihood is thus proportional to the product over all cells of the cell probability raised to the power corresponding to the observed number of recaptures in the cell. (Note that there is an implicit column of cells for fish never recaptured; this must be included in the likelihood.)

Estimation can be accomplished as follows: For the fishery component with planted tags, the value of λ can be estimated from the planted tags; the value of δ is assumed known from the landings of all of the components. Therefore, the likelihood for the component with planted tags is equivalent to the likelihood for an instantaneous-rates formulation of the Brownie models (as described by Hoenig et al. 1998a); the only difference is the inclusion of the δ and λ factors, which are known and estimable, respectively. Hence, the values of the fishing and natural mortality rates can be estimated from the data from the fishery component with the planted tags. For the other fishery components, δ is known from landings data and estimates of *F*, *M*, and *u* are available from the data for the component with planted tags. Therefore, all that remains is to relate the observed number of recaptures to the expected number by appropriate choice of the reporting rate, λ_k, for fishery component *k*. Let the component of the fishery with the planted tags be denoted as component 1. Assuming that each planted fish represents an independent Bernoulli trial, the maximum likelihood estimate of the tag reporting rate for this fishery component in year *j* is

$$\hat{\lambda}_{j1} = \frac{R^p_{j1}}{N^p_{j1}}, \quad (1)$$

where N^p_{j1} is the number of tags planted in the catch from component 1 in year *j* and R^p_{j1} is the number of tags reported from the plantings. Given this estimate of the reporting rate, the reporting rate from any other component in year *j* can be estimated by the equation (see Appendix 1)

$$\hat{\lambda}_{jk} = \frac{\delta_{j1}}{\delta_{jk}} \cdot \frac{\sum_{i=1}^{j} R_{ijk}}{\sum_{i=1}^{j} R_{ij1}} \cdot \frac{R^p_{j1}}{N^p_{j1}} = \frac{\delta_{j1}}{\delta_{jk}} \cdot \frac{\sum_{i=1}^{j} R_{ijk}}{\sum_{i=1}^{j} R_{ij1}} \cdot \hat{\lambda}_{j1}, \quad (2)$$

where R_{ijk} is the number of tags reported by component *k* during year *j* from fish that were tagged in year *i*. (Essentially, the middle factor in the right-hand side of the above equation is the ratio of all recaptures from the two components in year *j*.)

Assumptions

All the assumptions required for use of an instantaneous-rates formulation of the Brownie models (Hoenig et al. 1998a) are required for the multiple-component model with planted tags. These assumptions have been reviewed by Pollock et al. (2001):

(1) The tagged sample is representative of the population being studied. This implies that fish are thoroughly mixed, so that all fishery components have the same catch rate of tagged fish per unit of catch (tags/catch).

(2) There is no tag loss from fish.

(3) Survival rates are not affected by tagging. (Short-term tag loss and tag-induced mortality can be evaluated by means of holding experiments, e.g., Latour et al. 2001.) With respect to assumptions 2 and 3, it is noted that there are sometimes differences in the proficiency of taggers (Hearn et al. 1991) that are ideally mitigated by strict tagging protocols.

(4) The fishery component and time of recapture of each tagged fish is reported correctly, that is, the recapture is tallied in the correct cell of the recovery matrix. (Sometimes tags can be returned several years after the fish are recaptured.)

(5) The fate of each tagged fish is independent of the fates of other tagged fish.

(6) All tagged fish within a release cohort have the same annual survival and recovery rates.

(7) The instantaneous fishing and natural mortality risks are additive. Five additional assumptions are needed for the planted-tag method with multicomponent fisheries:

(8) The catch data for each component of the fishery are accurate. (In particular, there is no underreporting of the catch in some components.)

(9) The tags are planted surreptitiously and fishers do not see any tags being planted (otherwise the behavior of fishers might be altered). This almost certainly precludes the use of planted tags in recreational fisheries because there would probably be no opportunity to plant the tags without being seen. This assumption does not apply if the tags are detected automatically by machine.

(10) The planted tags are identical to the normal tags and are placed in such a way as not to look unusual (otherwise the behavior of fishers might be altered). For example, using planted tags with sequential numbers would be problematic.

(11) Planted tags are rare in any individual fisher's catch (the occurrence of an unusually high number of tags might change the behavior of fishers), and they cover all years.

(12) The tags are planted early enough after fish are caught that no part of the process for finding and reporting normal tags is omitted.

Matlock (1981) describes scientists secretly planting a tag into a fish in creels. Most fishers were contacted later and few knew or suspected that the tags were planted. However, this validation process would make fishers aware of scientists' real purpose, so it would not be feasible for multiyear tagging projects.

Test of Assumptions

If tagged fish are planted in all components of a fishery and their catches are given, the assumptions of the tagging model can be tested. The intuitive argument is as follows: The tags planted in each fishery component can be used to estimate that component's tag reporting rate. For each component, the tag recovery rate per fish landed can then be converted into the rates of tagged fish captured per fish landed (tags/catch) by dividing by its estimated reporting rates. For example, if 2 tagged fish are reported per 1,000 fish landed and the estimated tag reporting rate is 0.5, then we estimate that 4 (i.e., 2/0.5) tagged fish were caught per 1,000 landed.

The estimate of tags/catch for component k in year j is therefore

$$\hat{T}_{jk} = \frac{\hat{\alpha}_{jk}}{\hat{\lambda}_{jk}} = \frac{\sum_{i=1}^{j} R_{ijk}}{C_{jk}} \bigg/ \left(\frac{R^p_{jk}}{N^p_{jk}}\right), \qquad (3)$$

where $\hat{\alpha}_{jk}$ is the tags returned/catch (i.e., not adjusted for the reporting rate) and C_{jk} is the catch.

Assuming that the normally tagged fish are fully mixed in the catch, the catches are correctly tabulated, and the tag planting is implemented correctly in all components, in a particular year j the estimates of $\hat{T}_{jk}$ should be the same for all K components. It is important to note that equation (3), which is used for the estimation of $\hat{T}_{jk}$, requires only data that is entirely collected within component k (i.e., independently of other components). This allows us to examine the $\hat{T}_{jk}$ residuals, as shown in Appendix 2. If some of the residuals are large, this casts doubt on the assumptions.

Simulation Studies

We used the SURVIV program (White 1983) to simulate observations from fisheries with specific characteristics. In this approach, the user specifies a formula for the expected values for each cell of the recovery matrix and the number of planted tags recovered; the program then generates 1,000 samples from multinomial distributions with the specified parameters. We simulated tag recoveries from a study with 3 years of tagging data and 4 years of recapture data, assuming a type 2 fishery. The fishery consisted of two components. Parameters held constant over all scenarios were as follows:

$F_1 = F_2 = F_3 = F_4 = 0.3$/year;

$M = 0.2$/year;

N^p (the number of fish with planted tags each year) $= 50$; and

N (the number of normally tagged fish each year) $= 1{,}000$.

The tag reporting rates, λ, and the fraction of the total catch taken by the first component, δ, were held constant over time but varied among scenarios as follows:

Experiment 1.—The values of λ_2 and δ were held constant at 0.4 and 0.3, respectively; the value of λ_1 was varied from 0.1 to 1.0.

Experiment 2.—The values of λ_1 and λ_2 were held constant at 0.8 and 0.4, respectively; the value of δ was varied from 0.1 to 1.0.

Experiment 3.—The value of λ_2 was held constant at 0.4, and the expected number of tags recovered from the first fishery component was held constant ($\lambda_1\delta = 0.24$) as the value of λ_1 was varied among scenarios from 0.24 to 1.0.

Experiment 4.—The values of λ_1 and δ were held constant at 0.8 and 0.3, respectively; the value of λ_2 was varied from 0 to 1.0.

For each of the 1,000 samples in every scenario, we estimated all four fishing mortality rates, the natural mortality rate, and both tag reporting rates. We knew a priori that the maximum likelihood parameter estimates were asymptotically unbiased, and in all our simulations except one the means of the estimated parameter values were close to the actual parameter values. The one case with bias was due to estimating a parameter close to the boundary of the parameter space (i.e., estimating λ_2 when it was close to 1.0); we discuss this in Results. Therefore, we focus on the coefficients of variation (CVs) of the parameter estimates, which are defined as 100·SD/mean.

Results

For experiment 1, the CVs of all the parameter estimates are plotted against λ_1 (Figure 1). Similarly, the CVs from experiments 2, 3, and 4 are plotted against δ, λ_1, and λ_2 in Figures 2, 3, and 4, respectively. The CVs of all parameter estimates decline with increases in the value of λ_1 (Figure 1), δ (Figure 2), λ_1 and δ (Figure 3), and λ_2 (Figure 4), with one exception: the CV of the estimates of λ_2 in experiment 2 first decreases and then increases as δ increases (Figure 2).

In the simulation results from experiment 4, a

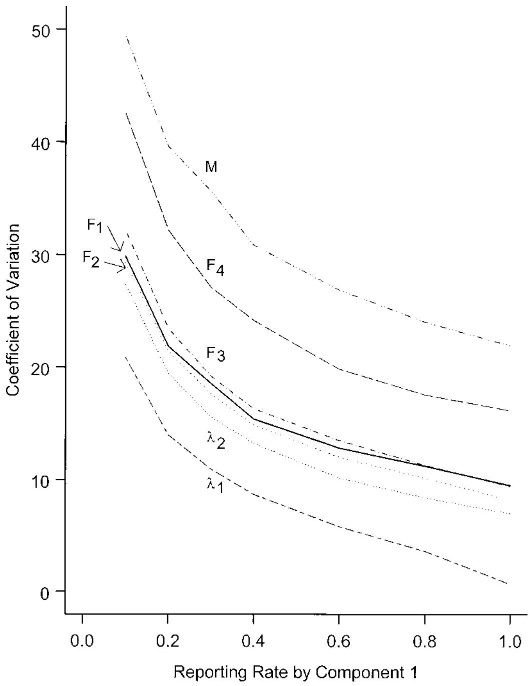

FIGURE 1.—Effects on the coefficients of variation of the parameter estimates that result from varying the tag reporting rate of fishery component 1 (λ_1), the component with planted tags. Other variables are defined as follows: M = the natural mortality rate per year of fish in the fishery; F_1–F_4 = the fishing mortality rates of fish recaptured in years 1–4; and λ_2 = the tag reporting rate of fishery component 2.

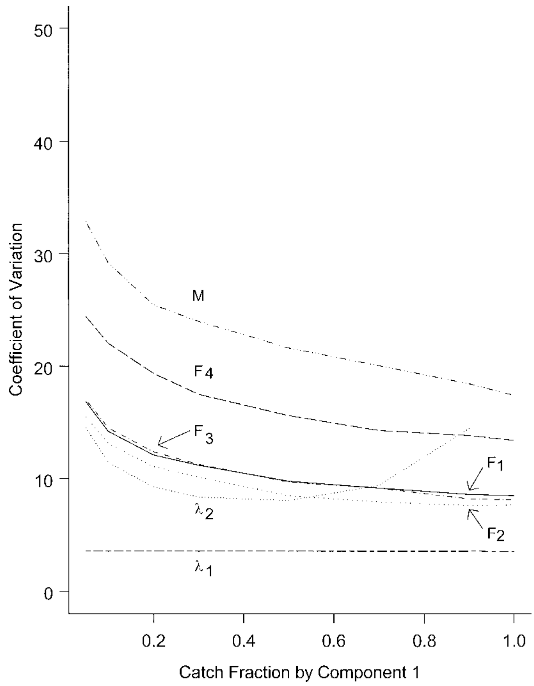

FIGURE 2.—Effects on the coefficients of variation of the parameter estimates that result from varying the fraction of the total catch that is taken by fishery component 1 (δ).

bias occurred in the estimate of λ_2 when the actual value of λ_2 was close to 1.0. For example, at an actual value of 1, the mean of the estimates from the simulation was 0.967, which represents a negative bias. This came about because the estimate of λ_2 (from equation 2) was less than 1.0 in about one-half of the simulated data sets while it was equal to 1.0 in the others (a reporting rate greater than 1.0 was not possible). Thus, the mean estimate was appreciably less than 1.0. This also resulted in a reduction of the coefficients of variation of the estimates of λ_2 when λ_2 was close to 1.0 (Figure 4). In normal fisheries we do not expect the reporting rates to be close to 1.0, so this does not appear to be a major problem.

Note that in experiments 1 and 3 the λ_1 estimates were not biased when they were set equal to 1.0 (Figures 1, 3). This is because λ_1 is estimated directly from the planted tags (equation 1), so that if λ_1 = 1.0 the estimate of λ_1 will always be 1.0. In summary, the difference between the bias characteristics of the two reporting rate estimates is due to the fundamental properties of their estimating equations and the data analyzed.

For the case with λ_1 = 0.8, λ_2 = 0.4, and δ = 0.3, which was common to all of the experiments, we ran the simulated experiment with 25 planted tags per year (i.e., one-half the planted tags). The CV of λ_1 increased by 38%, which would be expected because λ_1 is directly estimated from the planted tags (equation 1) and the number of observations was halved. However, the CVs of F_1 to F_4, M, and λ_2 increased by less than 9% compared with those derived from the experiment with 50 planted tags per year.

Discussion

Design Considerations Based on the Simulations

The precision of the mortality and tag reporting rate estimates increased markedly as the reporting rate of the fishery component with planted tags (λ_1) approached 1.0 (Figure 1). Similarly, precision improved for all parameters except λ_2 as the fraction of the total catch taken by component 1 approached 1.0 (Figure 2). An intuitive explanation for these results is that the normal tags returned from the second component provide infor-

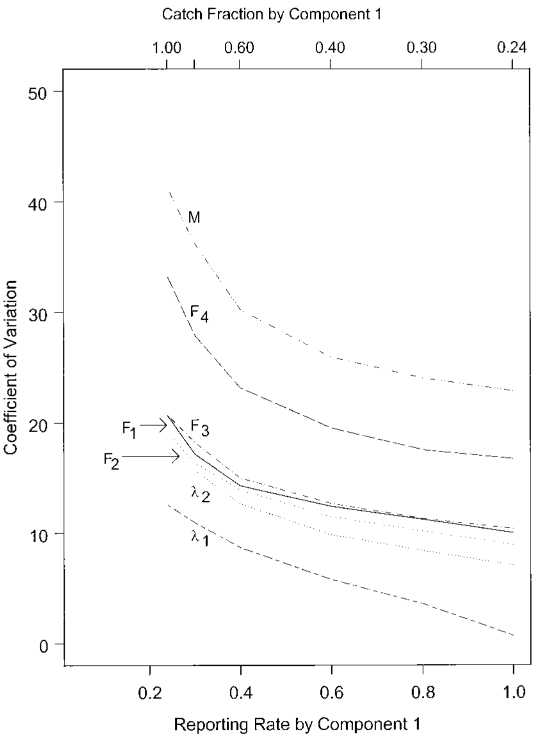

FIGURE 3.—Effects on the coefficients of variation of the parameter estimates that result from varying δ and λ_1 while the product $\delta\lambda_1$ is held constant. A constant product implies that the number of tags recovered from component 1 is constant.

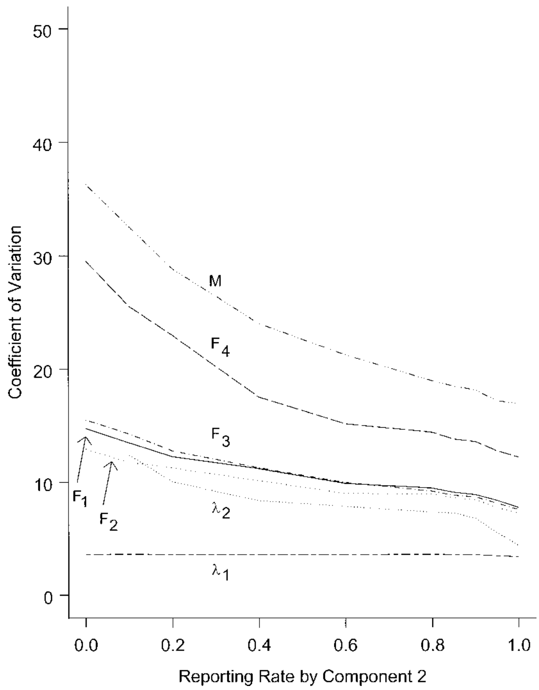

FIGURE 4.—Effects on the coefficients of variation of the parameter estimates that result from varying λ_2. Note that the coefficient of variation of λ_2 at $\lambda_2 = 0$ is 0/0 (i.e., undefined).

mation on the survival rate (or equivalently, the sum $F + M$) but extremely little information on tag reporting rate (and thus extremely little information on how to apportion the total mortality rate to its components). By contrast, the tag returns from the first component provide information on the sum $F + M$ as well as information on how to apportion the total mortality to its components. Therefore, the larger the fraction of the normal tags returned by component 1 (because either λ_1 or δ or both are high), the better the precision.

It was previously noted that the CV of the estimates of λ_2 in experiment 2 first decreases and then increases as δ increases (Figure 2). This can be established analytically from equation (2). Intuitively, it is because estimation of λ_2 depends on there being tag returns for both fishery components; the number of normal tags returned by component 1 becomes small when δ is close to zero, and the number of normal tags returned by component 2 also becomes small when δ is close to 1.0.

Our third experiment held the product $\delta\lambda_1$ constant. This implies that the expected number of tags recovered from component 1 was held constant. Here, precision varied considerably as δ and λ_1 varied, even though the product was constant (Figure 3). This shows that the size of λ_1 is more important than that of δ in determining the precision of the estimates. Thus, it is generally better to plant tags in the components with high reporting rates. This might appear to go against common sense, as one might intuitively expect it to be more effective to secretly check on the bad guys (the component with the low reporting rate) than the good guys (the component with the high reporting rate). By way of illustration, consider a component with 100% reporting, though this is unknown to scientists. Planted tags in that component will readily and efficiently reveal that fact to a high precision. At the other extreme, consider a component with a 0% reporting rate. That fact will be known without planted tags, but it brings no information to the estimation of the mortality parameters.

In experiment 4, we varied the value of λ_2 while holding everything else constant. The higher the tag reporting rate from the fishery component without the planted tags, the better was the precision of the estimates (Figure 4). Even though it is possible to estimate *F, M,* and *u* without considering the normal tagging data from the components with no planted tags (see CVs of parameters in Figure 4 when the reporting rate by component 2 is 0%), the additional data from these components will improve the precision of the estimates. This is because the data from the components without planted tags provide information about the survival rate, *S,* or equivalently, about the sum $F + M$.

The simulation results lead us to the conclusion that the method described in this article will work best when (1) the tag reporting rate (λ) in the fishery component with the planted tags is close to 1.0; (2) the component with the planted tags comprises a large fraction of the total fishery (δ is close to 1.0); and (3) the tag reporting rate in the component without the planted tags is close to 1.0 (though this is a secondary consideration).

Mixing Assumption

All fishery components must have the same catch rate of tagged fish (tags/catch). For example, the expected catch rate of tagged fish for all fisheries might be 2 tagged fish per 10,000 fish caught. This implies that the tagged fish are randomly distributed over the population, so that a decision by the fleet captains of one component to fish in a particular area has no influence on the catch rate of tagged fish per landed fish. (Obviously, the catch of fish per unit effort will be affected.) This assumption can be met if fish are tagged throughout the area inhabited by the stock in proportion to their local abundance. Local abundance can be judged in terms of local catch per unit effort. For example, if specimens are obtained with a trawl, it would be appropriate to tag 20% of the catch from each tow but not to tag 20 fish from each tow. Another way to help assure that the assumption is met is to tag fish well before the start of the fishing season so that tagged fish have a chance to mix randomly throughout the population (though even then such factors as schooling behavior might impede thorough mixing). Still another way is to assume that mixing occurs after a delay, in which case the data analysis method would be adjusted as described in Hoenig et al. (1998b).

Model Checking Using Residuals

If tagged fish are planted in two or more components of a fishery, the tagging model can be checked for violations of the assumptions. In Appendix 2, we derive a method to check for the equality of tags/catch in the various components that have planted tags. A large discrepancy between the estimates could be due to several factors. The first is the failure of tagged fish to mix throughout the population. This would cause bias in any model that does not allow for nonmixing, such as a Brownie model. The second is incorrect tabulation of catches of the various fishery components. For example it may be due to a poor data collection and processing procedure, deliberate deception by fishers, illegal fishing, or ghost fishing by lost nets. This would not cause bias in Brownie models because such models do not use catch data. However, in the instantaneous-rates models of this paper or Hearn et al. (1999), an error that affects one fishing component more than another will lead to bias in the estimate of δ (and hence in the estimates of the mortality rates). Catch errors would also be of concern in the assessment and management of the stock (e.g., allocation of quota).

A third factor that would lead to biased estimates is poor implementation of the tag planting procedure in some of the fishery components. For example, fishers in one component might return all tags whenever observers or planters are present but return few tags at other times. In an extreme case, all planted tags might be returned when only 50% of the normal tags are returned. For this component, the estimated number of recaptured tagged fish would be underestimated by 50%.

Note that researchers may attempt to plant tags in several (or all) fishery components and later it may be found that assumptions 9−12, which pertain to planted tags, cannot be (or have not been) complied with for some components. In such a case the entire study is not ruined, you just need it to work for one component (if you know the catches by component). However, then one cannot check for assumption violations as just described.

Bernoulli Assumption of Planted Tags

The Bernoulli assumption is not likely to be met. For example, if two tags are planted at the same place and at about the same time, their probabilities of being found and returned are likely to be dependent. In the extreme case, in which the tags are either both returned or both not returned, it is as if only one tag were planted (i.e., as if only one-half of the tags were planted). In the Results section a case was considered in which half the number of tags was planted, and it was found that apart from λ_1 the CVs of the parameters increased by no more than 9%. It is clear from Figures 1–4 why this is so. We planted a sufficiently high number of tags that the CV of λ_1 is substantially less than those of the other parameters. Thus, the variance of λ_1 has only a weak effect on the variances of the other parameters. This insures that an incorrect statistical model for λ_1 will have minimal effect, or conversely, that a correct model will not result in parameter variances that are too high for meaningful population inferences.

As the homogeneity of reporting rates across boats cannot normally be assured, few tags should be planted in many catches rather than many tags in few catches. Also, as a logistical matter, fishers are less likely to detect the surreptitious planting of tags if only a very few tags are planted at a time so that the number of tags encountered does not rise dramatically. To construct an adequate statistical model for λ_1, it is recommended that auxiliary information, such as the date, place, vessel, and personnel, be collected when planting and recovering tags.

In reality, planted-tag studies involve a multistage sampling process. That is, within each year vessel trips are selected within weeks, fishing sets are selected within trips, and tags are planted within sets. Because there can be enormous variability in fisher behavior among boats, the actual variability in tag reporting rate will be greater than that predicted from the binomial model assumed in this paper. The user of planted tags should therefore plan to plant more tags than the number called for under the Bernoulli assumption.

Other Discussion Points

In our simulations we planted tags in each year, but we have assumed that λ_1 is the same for all years. In a field study, if tags are planted in all years, the standard likelihood ratio test will allow testing for differences in λ_1 between years.

Use of planted tags is a powerful method but is difficult to implement in sufficient numbers. The requirement for secrecy in planting tags is the greatest obstacle and probably precludes its use in recreational fisheries. If the tags are automatically detected by a machine, then secrecy is not required. Another difficulty in commercial fisheries is that the catching, handling, and processing of fish is often a complex multistaged process. Unless tagged fish are planted in catches before the fish are first inspected by people, some component of the reporting process will be ignored. If normal tags that are found before tags are planted are all returned, then the overall reporting rate will be underestimated. If some or all of those tags are not returned, it is possible for the overall reporting rate to be overestimated.

Many fisheries are age structured, and this should be taken into account as described in Hearn et al. (1999). For our method, this implies that the age of each planted fish needs to be determined, say by measuring its length and using an age−length key or taking scales to allow direct aging.

A major problem with the method we described lies in the assumptions that the catch information is accurate, which implies no bias (which we have previously discussed) and that the statistical uncertainty in estimating the catch (and hence δ) is negligible. The latter is a wider problem that impinges on stock assessments and the method of estimating the reporting rate from tags found by scientific observers (Hearn et al. 1999). Collecting catch information often involves a multistage sampling process, which needs to be taken into account.

However, if variance information is available on catches it may be incorporated into our method. Where $\lambda_1 = 1.0$, we note that the estimate of λ_2 from equation (2) is identical to that for an observer program (Hearn et al. 1999 [equations 5 and 6]). This means that the technique of expressing the likelihood as a product of likelihoods involving reporting rates, catches, and mortalities also applies to our model (Pollock et al. 2002a). Pollock et al. (2002a) discuss how to incorporate catch variances into the procedure for estimating reporting and mortality rates.

Another connection to the observer approach is that the agents planting tags could possibly serve as observers so that the number of tagged fish per 1,000 fish landed (i.e., tags/catch) could be estimated. However, compared with the planted-tag information, this contribution to increased precision would probably be trivial. It might, however, detect serious bias, as might a modest high-reward program.

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Appendix 1: Derivation of Estimators for the Tag Reporting Rate in a Two-Component Fishery

Consider a fish population just before fishing begins. The size of the population is P, and there are R tagged fish in the population from previous tagging events; both P and R are unknown parameters. Let u_1 and u_2 be the finite exploitation rates for the (assumed) two components of the fishery, and let λ_1 and λ_2 be the corresponding tag reporting rates. The data collected are as follows:

C_1, C_2 = the catches in the two fishery components

R_1, R_2 = the number of tagged fish reported in the two components

N_1^p = the number of tagged fish planted in the first component

R_1^p = the number of planted fish reported from the first component

Full Likelihood

Under the assumption that the actual catches are random variables governed by a multinomial distribution with parameters P, u_1, and u_2, the likelihood of obtaining catches C_1 and C_2 is multinomial:

$$\begin{bmatrix} P \\ C_1, C_2 \end{bmatrix} (u_1)^{C_1}(u_2)^{C_2}(1 - u_1 - u_2)^{P-C_1-C_2}.$$

The number of reported recaptures of previously tagged fish is also multinomial, with parameters R, $u_1\lambda_1$, and $u_2\lambda_2$. Thus, the likelihood is

$$\begin{bmatrix} R \\ R_1, R_2 \end{bmatrix} (u_1\lambda_1)^{R_1}(u_2\lambda_2)^{R_2}(1 - u_1\lambda_1 - u_2\lambda_2)^{R-R_1-R_2}.$$

The number of planted tags that are reported is binomial, with parameters N_1^p and λ_1. Thus, the likelihood is

$$\begin{bmatrix} N_1^p \\ R_1^p \end{bmatrix} \lambda_1^{R_1^p}(1 - \lambda_1)^{N_1^p - R_1^p}.$$

The likelihood for all of the data is the product of the above three likelihoods.

Conditional Likelihood

If we condition the likelihood on the total catch, then the catch for each component is binomial with parameters $C_1 + C_2$ (known) and $u_1/(u_1 + u_2)$. Thus, the likelihood for the two catches given that the total catch is binomial is

$$\begin{bmatrix} C_1 + C_2 \\ C_1 \end{bmatrix} \left(\frac{u_1}{u_1 + u_2}\right)^{C_1} \left(\frac{u_2}{u_1 + u_2}\right)^{C_2}.$$

Similarly, we can condition on the total number of recaptures. In that case the number of recaptures from each component is binomial with parameters $R_1 + R_2$ (known) and $u_1\lambda_1/(u_1\lambda_1 + u_2\lambda_2)$, so that the likelihood is

$$\begin{bmatrix} R_1 + R_2 \\ R_1 \end{bmatrix} \left(\frac{u_1\lambda_1}{u_1\lambda_1 + u_2\lambda_2}\right)^{R_1} \left(\frac{u_2\lambda_2}{u_1\lambda_1 + u_2\lambda_2}\right)^{R_2}.$$

The likelihood for the planted tag recoveries does not depend on the other parts of the likelihood and remains binomial:

$$\begin{bmatrix} N_1^p \\ R_1^p \end{bmatrix} \lambda_1^{R_1^p}(1 - \lambda_1)^{N_1^p - R_1^p}.$$

The moment and maximum likelihood estimators are based on the following equations:

$$E(C_1 | C_1 + C_2) = (C_1 + C_2)\frac{\hat{u}_1}{\hat{u}_1 + \hat{u}_2} \quad (1.1)$$

$$E(R_1 | R_1 + R_2) = (R_1 + R_2)\frac{\hat{u}_1\hat{\lambda}_1}{\hat{u}_1\hat{\lambda}_1 + \hat{u}_2\hat{\lambda}_2} \quad (1.2)$$

$$E(R_1^p) = N_1^p\hat{\lambda}_1 \quad (1.3)$$

Equation (1.3) implies that

$$\hat{\lambda}_1 = \frac{R_1^p}{N_1^p}.$$

From (1.1)

$$\left(\frac{\hat{u}_1}{\hat{u}_2}\right) = \frac{C_1}{C_2},$$

and from (1.2)

$$\frac{\hat{u}_1\hat{\lambda}_1}{\hat{u}_2\hat{\lambda}_2} = \frac{R_1}{R_2}.$$

Therefore, if $\hat{\lambda}_2$ is greater than 1.0, the likelihood should be maximized subject to the constraint that $\hat{\lambda}_2 \leq 1.0$.

$$\hat{\lambda}_2 = \hat{\lambda}_1\left(\frac{\hat{u}_1}{\hat{u}_2}\right)\left(\frac{R_2}{R_1}\right) = \hat{\lambda}_1\left(\frac{C_1R_2}{C_2R_1}\right).$$

Appendix 2: Model Checking Using Residuals of Fishery Component Tags/Catch Rates

One approach to the testing problem is to standardize the estimated tags/catch for each fisheries component so that it has approximately a standard normal residual and a standard normal table can be used to see if the residual is unusual. (For example, if the model were valid, a residual larger than 1.96 in absolute value would occur approximately 1 time in 20; similarly, a residual larger than 2.57 would occur 1 time in 100.)

From equation (3) in the text, the estimate of the tags/catch common to all fisheries components is

$$\hat{T}_{jk} = \frac{\sum_{i=1}^{j} R_{ijk}}{C_{jk}} \Bigg/ \left(\frac{R^p_{jk}}{N^p_{jk}}\right) = \frac{\hat{\alpha}_{jk}}{\hat{\lambda}_{jk}}.$$

Note that here $\hat{\lambda}_{jk}$ is estimated from equation (1) rather than equation (2), with k replacing 1. This is because in this instance component k has planted tags, whereas in developing equation (2) it was assumed that component k ($k \neq 1$) had no planted tags.

Define the standardized residual to be

$$\hat{Q}_{jk} = \frac{\hat{T}_{jk} - \left(\sum_{m'=1}^{K} \hat{T}_{jm'} \Big/ K\right)}{\sqrt{\widehat{\text{var}}(\hat{T}_{jk})}},$$

where m refers to the mth fishery component and

$$\widehat{\text{var}}(\hat{T}_{jk}) = (\hat{T}_{jk})^2\left(\frac{\widehat{\text{var}}(\hat{\alpha}_{jk})}{(\hat{\alpha}_{jk})^2} + \frac{\widehat{\text{var}}(\hat{\lambda}_{jk})}{(\hat{\lambda}_{jk})^2}\right), \quad \text{with}$$

$$\widehat{\text{var}}(\hat{\alpha}_{jk}) = \hat{\alpha}_{jk}\,(1 - \hat{\alpha}_{jk})/C_{jk} \quad \text{and}$$

$$\widehat{\text{var}}(\hat{\lambda}_{jk}) = \hat{\lambda}_{jk}(1 - \hat{\lambda}_{jk})/N^p_{jk}.$$

This test can be readily adjusted for the case in which tags are planted in two or more components but not all components. However, it cannot be used to test the assumptions pertaining to components with no planted tags.