Estimation of fishing and natural mortality from tagging studies on fisheries with two user groups[1]

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Abstract: We present generalizations of fishery models that allow for the separate estimation of fishing mortality when more than one user group is present (e.g., a commercial and a recreational fishery). This model also allows for the fisheries to be in operation for any length of time whereas previously fisheries were generally considered to be pulse or continuous. Three cases are considered: (*i*) fisheries operate consecutively, (*ii*) fisheries overlap for a part of their seasons, and (*iii*) fisheries are in operation for the whole year. The results of a simulation study are included, which provide estimates of fishing and natural mortality along with their proportional standard errors (CVs). All scenarios had good precision, with most CVs < 25% and usually very little difference between the three cases. Coefficients of interaction, the potential gain by one fishery if another is closed down, are also given along with a method for calculating them. Factors affecting these coefficients of interaction were the order in which fisheries operated, amount of overlap in fishing seasons, and intensity of fishing effort by each fishery. We believe that these models could provide useful information for the management of fisheries with multiple user groups where allocation conflicts may arise.

Résumé : Nous présentons des généralisations de modèles halieutiques qui permettent l'estimation séparée de la mortalité par pêche quand il y a plus d'un groupe d'utilisateurs (pêche commerciale et pêche sportive). Ce modèle peut aussi prendre en considération des pêches de toute durée, tandis qu'antérieurement, on considérait généralement des pêches soit pulsatoires soit continues. Trois cas ont été considérés : (*i*) pêches consécutives, (*ii*) pêches chevauchantes durant une partie de leurs saisons et (*iii*) pêches qui ont lieu durant toute l'année. Nous présentons les résultats d'une étude de simulation qui fournit des estimations de la mortalité naturelle et de la mortalité par pêche avec leurs erreurs-types proportionnelles (CV). Nous avons obtenu une bonne précision dans tous les scénarios, la plupart des CV étant inférieurs à 25% et les différences entre les trois cas étant généralement très faibles. Nous présentons aussi les coefficients d'interaction, soit le gain potentiel d'une des pêches si l'autre est fermée, de même qu'une méthode pour les calculer. Les facteurs affectant ces coefficients d'interaction étaient l'ordre dans lequel les pêches étaient effectuées, le degré de chevauchement des saisons de pêche et l'intensité de l'effort de pêche dans chacune des pêches. Nous croyons que ces modèles peuvent fournir des informations utiles en vue de la gestion des pêches à groupes d'utilisateurs multiples dans lesquelles des conflits touchant les allocations peuvent survenir.

[Traduit par la Rédaction]

Introduction

Brownie et al. (1985) presented and summarized new and existing models for estimating survival rates in multiyear bird banding studies. These models have been extended to fisheries work in various formats since the 1970s, some of which permit the estimation of natural and fishing mortality in addition to yearly survival rates, provided an estimate of reporting rate is available (Youngs 1972; Youngs and Robson 1975; Jagielo 1991; Larson et al. 1991; Pollock et al. 1991; Dorazio 1993; Schwarz et al. 1993). Methods have also been introduced (Pollock et al. 1991) that allow for the estimation of instantaneous rates of mortality, as defined by Ricker (1975). However, to write down the expressions for the cells of the tagging/recovery matrix, one has to assume that a fishery is either Type I (pulse) or Type II (continuous). Hoenig et al. (1998*a*) have extended these models to include the use of effort as an auxiliary variable and also to generalize the pattern of fishing within the year. In another adaptation, Hoenig et al. (1998*b*) extended the models further to allow for nonmixing for all or part of the year of tagging.

These models were developed for one user group, although it may sometimes be the case that more than one user

Received February 6, 1997. Accepted March 4, 1998.
J13863

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Table 1. Matrix of expected recoveries for two user groups, commercial and recreational, under Brownie Model 1 for a tagging study with three tagging years and three recovery years.

Year tagged	No. tagged	Expected recoveries Year 1	Year 2	Year 3	Fishery type
1	N_1	N_1f_{11}	$N_1S_1f_{12}$	$N_1S_1S_2f_{13}$	Commercial
		N_1f_{21}	$N_1S_1f_{22}$	$N_1S_1S_2f_{23}$	Recreational
2	N_2		N_2f_{12}	$N_2S_2f_{13}$	Commercial
			N_2f_{22}	$N_2S_2f_{23}$	Recreational
3	N_3			N_3f_{13}	Commercial
				N_3f_{23}	Recreational

group is exploiting a given fish population, e.g., a commercial fishery and a recreational fishery. In this scenario, one would like to know what proportion of the total exploitation was due to each user group. This information would be valuable in terms of setting catch limits and designating fishing seasons for each user group. It could also be used to calculate an expected gain by one fishery if the other is mandated to reduce its catch or close down completely.

In addition to being able to generalize the original models to include more than one user group, one would also like to be able to generalize the type of exploitation to describe fishing seasons that do not fit the restrictive categories of pulse or continuous (Ricker 1975). It does not seem realistic to assume that all fisheries could be classified as either strictly pulse or strictly continuous. The timing of the two fisheries will have important implications for the form of the model.

We begin with a review of the statistical nature and notation of these models before discussing generalizations of the models for the two types of fisheries. Next, we present methods for separately estimating exploitation rates when there are two user groups. We initially consider the simpler case where only slow-growing adult fish are tagged; later, we present the modifications necessary for the case where growth is not negligible. In the former case, we assume that the catchability and natural mortality of the tagged fish do not depend on their age. We also consider gains if one fishery is closed by calculating coefficients of interaction. (While we use tagging data to look at interaction, Beverton and Holt (1957) considered yield per recruit (YPR) to investigate the consequences of various management strategies in a two user group continuous fishery. The YPR approach has been extended and applied in later papers, e.g., Murawski (1984) and Shepherd (1988). In another example, Horwood and Nicholson (1991) analyzed tagging data and catch information of Dover sole (*Microstomus pacificus*) that was harvested by fleets of three countries.) Next, we present an artificial example and a simulation study. Finally, we present a general discussion section that includes suggestions for future research.

Theoretical model development

Notation

We use the following notation: S_i is the finite annual survival rate or the probability of surviving year i; u_{ji} is the finite annual exploitation rate for fishery j (j = 1 or 2) or the probability of being harvested by fishery j in year i (note that u_{ji} can be viewed as the fraction of the fish present at the beginning of year i that is harvested by fishery j); λ_{ji} is the tag-reporting rate for fishery j in year i or the probability that a tag will be found and reported to the fisheries biologist, given that the tagged fish has been harvested by fishery j; $v_i = 1 - S_i - u_{1i} - u_{2i}$ is the finite natural mortality rate or the probability of dying from a natural cause in year i in the presence of fishing mortality; $f_{ji} = \lambda_{ji}u_{ji}$ is the tag-recovery rate or the probability of a tagged fish being harvested by fishery j and reported during year i; F_{ji} is the instantaneous fishing mortality rate (expressed on a yearly basis) for fishery j in year i; M_i is the instantaneous natural mortality rate for year i; and $Z_i = F_{1i} + F_{2i} + M_i = -\log_e(S_i)$ is the instantaneous total mortality rate for year i.

Model development

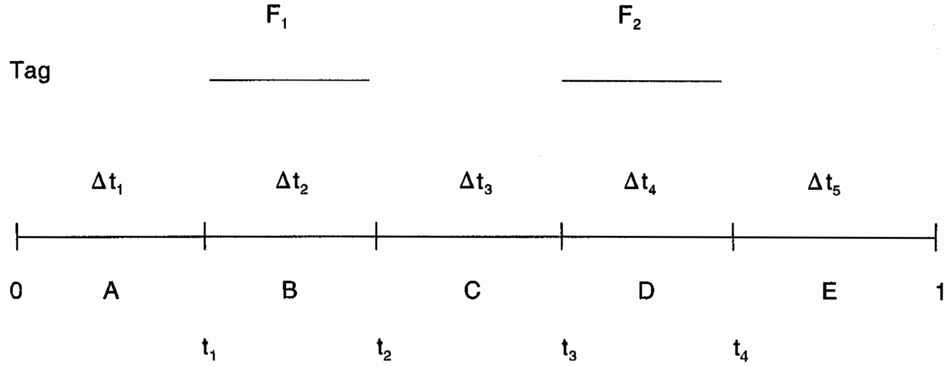
Our models are developed from the same statistical framework as those of Brownie et al. (1985). Those models can be used to estimate for data that have a multinomial distribution. The multinomial distribution describes data that have more than two outcomes (the binomial distribution, which has precisely two outcomes, is a special, well-known case of the multinomial). Tag- or band-recovery data are ideally fit to a multinomial distribution, since a tagged animal can either be caught or not caught in each year after it has been initially tagged. For k years after an animal has been tagged, there are $k + 1$ possible outcomes: there is a probability that it is caught in one of the k years, which gives k outcomes; the last probability is that it is not caught during the k years, and this is 1 – (sum of all probabilities of being captured).

There are many computer programs available that are capable of estimating the parameters specified in tag-return models. Most of these programs use maximum likelihood estimation (MLE) to estimate the parameters. MLE is an estimation procedure that finds the "most likely" estimates of parameters based on the observed data.

Of the models presented in Brownie et al. (1985), Model 1 refers to "well-mixed" populations, which means that newly tagged and previously tagged animals have the same recovery rate. For the generalization of Brownie's Model 1 to two user groups (e.g., commercial and recreational), the matrix of expected recoveries for a study with three tagging years and three recovery years is shown in Table 1. For this model, newly tagged and previously tagged fish have the same recovery rate in a given year. It would be possible to generalize to allow for nonmixing in the year of tagging along the lines of Hoenig et al. (1998*b*), but for simplicity of presentation, that case is not considered here.

It is possible to estimate the quantities f_{11}, f_{21}, f_{12}, f_{22}, f_{13}, f_{23}, S_1, and S_2. Following Brownie et al. (1985), the likelihood can be constructed by treating the rows of the recovery matrix as independent multinomial distributions with the expectations as in Table 1 (cf. Schwarz et al. 1988). Expressed in terms of the finite parameters f and S, Table 1 is the familiar poststratification band-recovery formulation (Schwarz et al. 1988). We use this formulation as a starting point for the development of our models, which will permit the reexpression of these finite rates in instantaneous terms of M and user-specific Fs.

Fig. 1. Generalized scenario for two user groups (1 and 2) with nonoverlapping seasons. The length of each subinterval A, B, C, D, and E is Δt_1, Δt_2, Δt_3, Δt_4, and Δt_5, respectively.



When an estimate of reporting rate, λ_{ji}, is available for each user group, it is then possible to obtain estimates of u_{1i} and u_{2i} (i = 1, 2, 3) by interpreting f_{ji} to be the probability a tagged fish is caught multiplied by the probability that the tag is reported given that the fish is caught, i.e., $f_{ji} = u_{ji}\lambda_{ji}$. An estimate of the reporting rate can be obtained through the use of high-reward tags, planted tags, or port/creel sampling (Pollock et al. 1991).

The following seven assumptions are required for the Brownie models: (*i*) the tagged sample is representative of the target population; (*ii*) there is no tag loss, or it can be accounted for by double tagging; (*iii*) survival rates are not influenced by tagging; (*iv*) the year of tag recovery is correctly tabulated; (*v*) the fate of each tagged fish is independent of the fate of other tagged fish; (*vi*) all tagged fish within a tagged cohort have the same annual survival and recovery probabilities in a given year; and (*vii*) the survival and recovery probabilities do not depend on the age of the animal (we relax this assumption later). In addition, we make the following assumptions for our models: (*viii*) the forces of instantaneous natural and fishing mortality (M and F) are additive and independent; (*ix*) natural mortality is constant within a year (no seasonal variation) and between years; (*x*) fishing mortality for a user group is constant for the period of the year that the fishery is operating; and (*xi*) tagging takes place over a short period. For a discussion of these assumptions as they relate to fish populations, see Pollock et al. (1991).

Generalization of pulse fishery: nonoverlapping seasons

Here, we present a generalization of a pulse fishery with two user groups, as pictured in Fig. 1. The user groups have nonoverlapping periods of exploitation.

For a given year (which is represented as an interval from $t = 0$ to $t = 1$, with tagging of fish occurring at time $t = 0$), we can write expressions for the us and Ss as follows:

$$u_1 = S_A\left(\frac{F_1}{F_1+M}\right)(1-e^{-(F_1+M)\Delta t_2})$$

$$u_2 = S_A S_B S_C\left(\frac{F_2}{F_2+M}\right)(1-e^{-(F_2+M)\Delta t_4})$$

where S_A, S_B, and S_C are the survival probabilities for periods A, B, and C, respectively, and

$$S_A = e^{-M\Delta t_1}$$

$$S_B = e^{-(F_1+M)\Delta t_2}$$

$$S_C = e^{-M\Delta t_3}$$

$$S_{TOTAL} = e^{-(F_1\Delta t_2+F_2\Delta t_4+M)}.$$

Notice that this formulation of competing risks follows directly from assumptions *viii*, *ix*, and *x* (see also Youngs 1972). The total exploitation, u_{TOTAL}, for both user groups is then

$$u_{TOTAL} = u_1 + u_2.$$

This formulation allows all equations to be expressed in terms of instantaneous fishing and natural mortality rates for which we can obtain MLEs by constructing multinomial likelihoods. That is, since each cell in the recovery matrix can now explicitly be expressed in terms of F and M, one can use the program SURVIV (White 1983) to get the MLEs of F_{ji} and M. SURVIV is specifically designed for estimating multinomial likelihoods. (Note that although we estimate only one M for all three years, it is possible to estimate two separate Ms but not all three; since at least two Ms must be equal, we decided to fix M to be constant for all 3 years.)

Generalization of pulse fishery: overlapping seasons

In Fig. 2, we have two user groups whose periods of exploitation overlap for part of the fishing season. Expressions for the us and Ss are

$$u_1 = S_A(1-S_B)\frac{F_1}{F_1+M} + S_A S_B(1-S_C)\frac{F_1}{F_1+F_2+M}$$

$$u_2 = S_A S_B(1-S_C)\frac{F_2}{F_1+F_2+M} + S_A S_B S_C(1-S_D)\frac{F_2}{F_2+M}$$

where

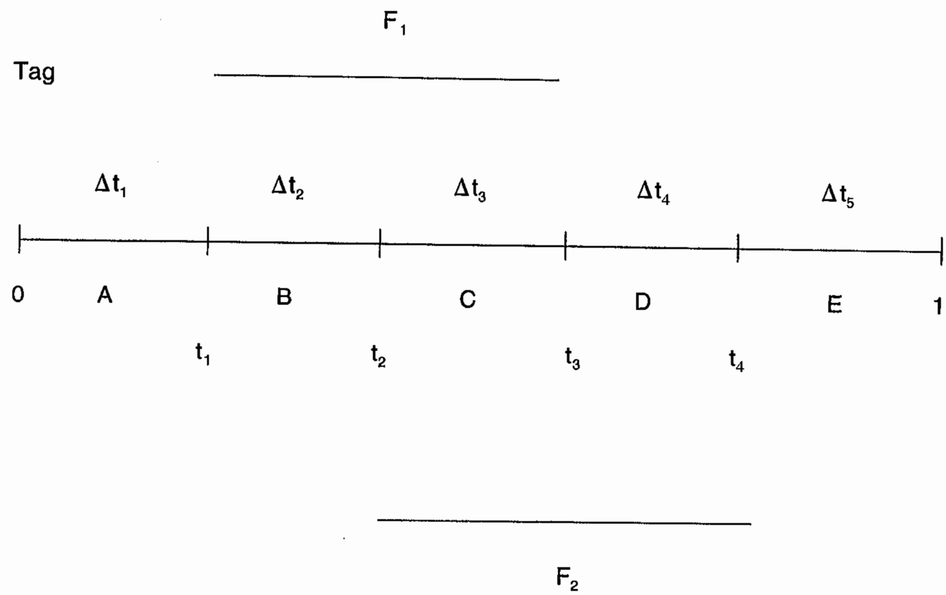
$$S_A = e^{-M\Delta t_1}$$

$$S_B = e^{-(F_1+M)\Delta t_2}$$

$$S_C = e^{-(F_1+F_2+M)\Delta t_3}$$

$$S_D = e^{-(M+F_2)\Delta t_4}$$

Fig. 2. Generalized scenario for two user groups (F_1 and F_2) with overlapping seasons. The length of each subinterval A, B, C, D, and E is Δt_1, Δt_2, Δt_3, Δt_4, and Δt_5, respectively.



$$S_{\mathrm{TOTAL}} = \mathrm{e}^{-[F_1(\Delta t_2+\Delta t_3)+F_2(\Delta t_3+\Delta t_4)+M]}.$$

The total exploitation is

$$u_{\mathrm{TOTAL}} = u_{\mathrm{B}} + u_{\mathrm{C}} + u_{\mathrm{D}} = u_1 + u_2.$$

(Note that u_{B}, u_{C}, and u_{D} are exploitations during periods B, C, and D, respectively.)

We can easily collapse this scenario into that of a pulse (Type I) fishery. If we first consider the case where we let t_3 approach ($\rightarrow$) t_2, then what we have is two user groups with no overlap, as previously considered. The total exploitation then becomes

$$u_{\mathrm{TOTAL}} = u_{\mathrm{B}} + u_{\mathrm{D}}.$$

Furthermore, letting $t_1 \rightarrow t_2$ and $t_4 \rightarrow t_3$, we have

$$u_1 = \mathrm{e}^{-Mt_1}(1 - \mathrm{e}^{-(F_1+F_2+M)\Delta t_3})\left(\frac{F_1}{F_1 + F_2 + M}\right)$$

$$u_2 = \mathrm{e}^{-Mt_1}(1 - \mathrm{e}^{-(F_1+F_2+M)\Delta t_3})\left(\frac{F_2}{F_1 + F_2 + M}\right)$$

Next, allowing $\Delta t_3 \rightarrow 0$, exploitation periods become small enough that essentially no natural mortality occurs. The total exploitation can then be written

$$u_{\mathrm{TOTAL}} = \mathrm{e}^{-Mt_1}(1 - \mathrm{e}^{-(F_1'+F_2')})$$

where F_1' and F_2' are the finite limiting values of $F_1\Delta t_3$ and $F_2\Delta t_3$ as F_1 and $F_2 \rightarrow \infty$ and $\Delta t_3 \rightarrow 0$. These finite limiting values can be interpreted by imagining a fishery with a season that lasts Δt_3. As that season gets shorter and shorter, the fishing intensity must increase to maintain the same harvest rate. The limiting values occur when we let the length of the season approach zero, in which case the fishing intensity in that instant is tremendous (approaching infinity). We can consider the product of the Fs and Δt_3 at these extreme values to be some fixed constant, which is denoted by F_1' and F_2'. Finally, letting $t_1 \rightarrow 0$, we are left with

$$u_{\mathrm{TOTAL}} = 1 - \mathrm{e}^{-(F_1'+F_2')}.$$

It should be clear from these two examples that the theory can be extended to any situation where you have two user groups simply by adjusting the Δts. For example, one can obtain expressions for two user groups that are both continuous (Type II). In Fig. 2, if we let t_1 and $t_2 \rightarrow 0$ and t_3 and $t_4 \rightarrow 1$, then we are left with the following expressions:

$$u_1 = \frac{F_1}{F_1 + F_2 + M}[1 - \mathrm{e}^{-(F_1+F_2+M)}]$$

$$u_2 = \frac{F_2}{F_1 + F_2 + M}[1 - \mathrm{e}^{-(F_1+F_2+M)}]$$

$$S_{\mathrm{TOTAL}} = \mathrm{e}^{-(F_1+F_2+M)}$$

$$u_{\mathrm{TOTAL}} = \frac{F_1 + F_2}{F_1 + F_2 + M}[1 - \mathrm{e}^{-(F_1+F_2+M)}] = u_1 + u_2.$$

Clearly the theory is also easily extended to more than two user groups, but we do not consider that here.

Estimation of potential gain from closing down one fishery

Having developed the means for estimating the proportion of fishing mortality that is due to each user group, one can ask what is the effect that one group has on the catch of the other (Sibert 1984; Majkowski et al. 1988; Kleiber 1994; Bertignac 1996; Hearn and Mazanov 1996). Suppose we have two fisheries, 1 and 2, that fish the same population. Total catches by each fishery during year i are denoted C_{1i} and C_{2i}. If fishery 1 is closed for n years, then its loss in catch in numbers is $\sum_{i=1}^{n} C_{1i}$. Consequently, the gain in catch in numbers for fishery 2 is $\sum_{i=1}^{n} C_{2i}^* - \sum_{i=1}^{n} C_{2i}$, where C_{2i}^* is the catch by fishery 2 in the absence of fishery 1. This gain will be some proportion of the loss by fishery 1, and we call this proportion the coefficient of interaction. We can calculate the approximate expected coefficient of interaction of fishery 1 on fishery 2 (IC 1 on 2) by

$$(1)\qquad E(\text{IC 1 on 2}) \approx \frac{E\left(\sum_{i=1}^{n} C_{2i}^* - \sum_{i=1}^{n} C_{2i}\right)}{E\left(\sum_{i=1}^{n} C_{1i}\right)}$$

which is the ratio of the expected gain in the catch of fishery 2 per unit loss of fishery 1. This assumes that the dynamics are linear, i.e., the rates of natural mortality and the fishing mortality of the continuing fishery are not affected by the closure of the other. This means that we assume that the closure of fishery 1 does not affect the catchability of fishery 2, nor does it change the ecology or the behavior of the fish or fishers. (This is satisfied if catch per unit of fishing is proportional to population numbers and the fishing effort of the remaining fishery is kept constant. Dramatic increases, however, could be limited by processing and carrying capacity of fishery 2.) In eq. 1, the expectations of the summations are simply the summations of the expectations. We can express these summations in terms of *u*s and *S*s as found in the analysis of the recovery matrix:

$$E\left(\sum_{i=1}^{n} C_{1i}\right) = P_1 \sum_{i=1}^{n} u_{1i} \prod_{k=0}^{i-1} S_{\text{TOTAL},k}$$

$$E\left(\sum_{i=1}^{n} C_{2i}\right) = P_1 \sum_{i=1}^{n} u_{2i} \prod_{k=0}^{i-1} S_{\text{TOTAL},k}$$

$$E\left(\sum_{i=1}^{n} C_{2i}^*\right) = P_1 \sum_{i=1}^{n} u_{2i}^* \prod_{k=0}^{i-1} S_{\text{TOTAL},k}^*$$

where $S_{\text{TOTAL},0} = 1$ and P_1 is the cohort population at the beginning of year 1. However, notice that P_1 is not needed to calculate an estimate for the interaction (eq. 1) because it cancels out of the ratio. This is significant because it is through the use of a tagging study (and the expectations for catch that are associated with it) that we are able to eliminate P_1 in eq. 1. Thus, we can estimate $E(C_{2i}^*)$, the potential catch in year *i* by fishery 2 given that fishery 1 is closed for all *i* years, by rewriting the *u*s and *S*s in terms of *F*s and *M*s according to the derivations from the previous section.

The interaction coefficient is in terms of numbers of fish. This may be of interest if growth is negligible. However, the calculations can be modified to allow for growth between the times of fisheries 1 and 2. Thus, eq. 1 can be replaced by

$$E(\text{IC 1 on 2}) \approx \frac{w_{2i} E\left(\sum_{i=1}^{n} C_{2i}^* - \sum_{i=1}^{n} C_{2i}\right)}{w_{1i} E\left(\sum_{i=1}^{n} C_{1i}\right)}$$

where w_{2i} and w_{1i} are the mean weights in fisheries 2 and 1, respectively, in year *i*. These weights can be determined empirically by sampling the catches in the fisheries. Notice that we take $w_{21}^* = w_{21}$. This is true when fishery 1 catches fish of a younger age than fishery 2 and there is no overlapping ages. In general, however, $w_{21}^* > w_{21}$.

Alternatively, the calculations can be done using a YPR model, since the interaction coefficients are essentially an analysis of the YPR under two conditions. The tagging data allow one to estimate all of the necessary parameters including natural mortality and growth. If ages cannot be assigned at the time of tagging, then relative ages can be determined a posteriori from the increments in size (e.g., Fabens 1965). For the calculation of the interaction coefficients, it does not matter if the ages are absolute or shifted by a constant number of years.

Referring back to the sample recovery matrix from the model development section where we had three tagging years and three recapture years, we would be able to estimate F_{1i}, F_{2i}, and M_i for i = 1, 2. Assuming $M_3 = M_2$, then we can also estimate F_{13}, F_{23}, and $S_{\text{TOTAL},3}$. If the tagging experiment does not proceed past i = 3 years, then one may assume that conditions for years >3 would be the same as in year 3 and so a geometric progression could be summed:

$$E\left(\sum_{i=1}^{n} C_{1i}\right) = EP_1 \times \left(u_{11} + u_{12} S_{\text{TOTAL},1} + u_{13} S_{\text{TOTAL},1} S_{\text{TOTAL},2} \frac{1 - S_{\text{TOTAL},3}^{n-2}}{1 - S_{\text{TOTAL},3}}\right)$$

with similar expressions for $E\left(\sum_{i=1}^{n} C_{2i}\right)$ and $E\left(\sum_{i=1}^{n} C_{2i}^*\right)$. If the tagging experiment continues for longer than 3 years, say to 4 years, then F_{14}, F_{24}, and $S_{\text{TOTAL},4}$ are estimable provided M_4 is known (e.g., $M_4 = M_3 = M_2$).

The expressions for $E(u_{2i}^*)$ and $E(S_{\text{TOTAL},i}^*)$ can be estimated by putting $F_{1i} = 0$ into the equations for u_{2i} and $S_{\text{TOTAL},i}$. Consequently, the coefficient of interaction of fishery 1 upon fishery 2 can be estimated by analyzing a suitably designed and executed tag-return experiment without any commercial catch or effort statistics.

Age-structured models

In general, fisheries target a mixture of age groups including some that are still actively growing. The fishing mortality rates of actively growing cohorts probably change as the cohorts become older and larger, e.g., because of net size selectivity. Brownie and Robson (1976) showed that it is possible to estimate age- and year-specific survival rates from

Table 2. Age-structured matrix of expected recoveries for two user groups for a tagging study with three tagging years and three recovery years.

Year tagged	No. tagged	Expected recoveries Year 1	Year 2	Year 3	Fishery type
Fish tagged and released at age *a*					
1	N_{1a}	$N_{1a}f_{11a}$	$N_{1a}S_{1a}f_{12a+1}$	$N_{1a}S_{1a}S_{2a+1}f_{13a+2}$	Commercial
		$N_{1a}f_{21a}$	$N_{1a}S_{1a}f_{22a+1}$	$N_{1a}S_{1a}S_{2a+1}f_{23a+2}$	Recreational
2	N_{2a}		$N_{2a}f_{12a}$	$N_{2a}S_{2a}f_{13a+1}$	Commercial
			$N_{2a}f_{22a}$	$N_{2a}S_{2a}f_{23a+1}$	Recreational
3	N_{3a}			$N_{3a}f_{13a}$	Commercial
				$N_{3a}f_{23a}$	Recreational
Fish tagged and released at age *a* + 1					
1	N_{1a+1}	$N_{1a+1}f_{11a+1}$	$N_{1a+1}S_{1a+1}f_{12a+2}$	$N_{1a+1}S_{1a+1}S_{2a+2}f_{13a+3}$	Commercial
		$N_{1a+1}f_{21a+1}$	$N_{1a+1}S_{1a+1}f_{22a+2}$	$N_{1a+1}S_{1a+1}S_{2a+2}f_{23a+3}$	Recreational
2	N_{2a+1}		$N_{2a+1}f_{12a+1}$	$N_{2a+1}S_{2a+1}f_{13a+2}$	Commercial
			$N_{2a+1}f_{22a+1}$	$N_{2a+1}S_{2a+1}f_{23a+2}$	Recreational
3	N_{3a+1}			$N_{3a+1}f_{13a+1}$	Commercial
				$N_{3a+1}f_{23a+1}$	Recreational
Fish tagged and released at age *a* + 2					
1	N_{1a+2}	$N_{1a+2}f_{11a+2}$	$N_{1a+2}S_{1a+2}f_{12a+3}$	$N_{1a+2}S_{1a+2}S_{2a+3}f_{13a+4}$	Commercial
		$N_{1a+2}f_{21a+2}$	$N_{1a+2}S_{1a+2}f_{22a+3}$	$N_{1a+2}S_{1a+2}S_{2a+3}f_{23a+4}$	Recreational
2	N_{2a+2}		$N_{2a+2}f_{12a+2}$	$N_{2a+2}S_{2a+2}f_{13a+3}$	Commercial
			$N_{2a+2}f_{22a+2}$	$N_{2a+2}S_{2a+2}f_{23a+3}$	Recreational
3	N_{3a+2}			$N_{3a+2}f_{13a+2}$	Commercial
				$N_{3a+2}f_{23a+2}$	Recreational

Note: To separate age and year effects, all ages must be tagged in all years. For this study, age-specific recovery rate can be estimated for ages *a*, *a* + 1, and *a* + 2 for years 1, 2, and 3. Age-specific survival can be estimated for ages *a* and *a* + 1 for years 1 and 2.

tagging data if the ages of the fish are determined at the time of tagging.

Consider the case where fish of age *a*, *a* + 1, and *a* + 2 are tagged each year and recoveries are recorded according to the age of initial tagging and release (see Brownie et al. 1985, p. 119). It can be seen from the table of expected recoveries (Table 2) that it is possible to estimate survival rates. For example, the survival rate of age *a* animals in year 1, S_{1a}, can be estimated from the ratio of returns for a given fishery:

$$\hat{S}_{1a} = \frac{R_{12a}}{R_{22a+1}} \times \frac{N_{2a+1}}{N_{1a}}$$

where R_{12a} are the tags returned in year 2 of fish tagged in year 1 at age *a* and R_{22a+1} are the tags returned in year 2 of fish tagged in year 2 at age *a* + 1. (Here, the returns could refer to returns from the commercial fishery, the recreational fishery, or both combined.) Similarly, the survival rate of age *a* + 1 animals in year 2 can be estimated by looking at the ratio of recoveries of animals tagged in years 2 and 3. It is clear that survival rates for all ages and all years (except the last age and the last year) can be estimated if all ages are tagged in all years.

As in the case without age structure, we can replace the *S*s with functions of the (now age-specific) *F*s and *M* as previously derived; also, we can replace the *f*s with products of $u\lambda$ and the *u*s with functions of the (age-specific) *F*s and *M*. Thus, each cell in the series of recovery matrices can be associated with a cell probability that is a function of the natural mortality rate, tag-reporting rate, and the series of fishing mortality rates that has been experienced by the cohort. The fishing mortality rates can be age, year, and user group specific. Depending on the data, the natural mortality rate can be made variable to some extent over age or time (see Hoenig et al. 1998*a*). Likewise, tag-reporting rates can be specified as variable if sufficient data are available to estimate each reporting rate.

Interaction coefficients can be calculated from the resulting estimates of fishing and natural mortality. The situation is, however, more complicated than for the non-age-structured case because exploitation varies both by age and time, rather than just by time. Consider first the immediate effects of the closure of fishery 1. The approximate expected value of the interaction coefficient in the year of closure is

$$E(\text{IC 1 on 2}) \approx \frac{\sum_{a=1}^{A} E(C_{1a})u_{2a}^{*}}{\sum_{a=1}^{A} E(C_{1a})}$$

where u_{2a}^{*} is the exploitation rate for fishery 2 in the absence of fishery 1. The new exploitation rate for fishery 2 can be calculated from the fishing mortality rate for fishery 2, the natural mortality rate, and information on the timing of the fishery (the fishing mortality rate for fishery 2 does not change if fishery 1 is eliminated). Thus, of the C_{1a} fish not caught due to the closure of fishery 1, the fraction u_{2a}^{*} of them will be caught that year by fishery 2.

Note that it is possible that the closure of fishery 1 has no immediate effect on fishery 2. This occurs, for example, if

Table 3. Example of a tagging/recovery matrix with three tagging years and three recovery years when a commercial and a recreational fishery are both present.

Year tagged	No. tagged	No. of recoveries			Fishery type
		Year 1	Year 2	Year 3	
1	1000	60	45	20	Commercial
		35	25	5	Recreational
2	850		50	30	Commercial
			20	10	Recreational
3	925			45	Commercial
				15	Recreational

Table 4. Maximum likelihood parameter estimates for instantaneous rates of fishing (F) and natural (M) mortality rate as computed using the program SURVIV (White 1983).

Parameter	Estimate	Estimated SE
F_{11}	0.1429	0.0196
F_{21}	0.0418	0.0073
F_{12}	0.1473	0.0194
F_{22}	0.0348	0.0059
F_{13}	0.1108	0.0173
F_{23}	0.0175	0.0038
M	0.1827	0.0791
IC 1 on 2	0.0407	0.0044
IC 2 on 1	0.1852	0.0131

fishery 1 harvests 3-year-olds, while fishery 2 harvests 4-year-olds. Thus, it is of interest to determine the effect of closure over various periods of time.

The cumulative interaction after 2 years can be defined to be the increase in catch of fishery 2 over the 2-year period per unit loss of catch from fishery 1 over the 2 years. Because present catch is more valuable than future catch, one may wish to discount the annual catches by an appropriate interest rate. The expected value of the cumulative interaction coefficient (CIC) can now be defined as

$$E(\text{CIC 1 on 2 (2 years)}) \approx \frac{\sum_{a=1}^{A}\sum_{t=1}^{2} E(C_{1at})u_{2at}^{*}w_{at} + \sum_{a=1}^{A-1} E(C_{1A1})S_{a1}^{*}u_{2,a+1,2}^{*}w_{a+1,t+1}\delta}{\sum_{a=1}^{A}\sum_{t=1}^{2} E(C_{1at})w_{at}\delta^{t-1}}$$

where δ is the discounting factor that is related to the interest rate i by $\delta = (1 + i)^{-1}$. Here, the denominator is the (discounted) loss to fishery 1 by the closure. The numerator is the gain to fishery 2. It has two parts: the immediate and the delayed gain. That is, some of the fish not taken by fishery 1 (because of the closure) will be harvested in year 1 and some will be harvested in year 2. The same approach can be used to extend the formula to the cumulative interaction over a longer period of time. This formulation is a simplification, however, and does not account for costs associated with handling, processing, and distribution.

Example

For illustrative purposes, we present an artificial example of a tagging/recovery matrix. Consider the example in Table 3 with three tagging years and three recovery years. We assume that these data came from two user groups that fished continuously, so that no adjustment for time scale is necessary for the estimated Fs. Using the program SURVIV (White 1983), we can obtain the MLEs of the parameters F_{1i}, F_{2i}, M_i, S_i (i = 1, 2), u_{13}, and u_{23}. For Type II fisheries in general, it is necessary to introduce a constraint on M for the last year to be able to estimate all of the Fs. We opted to constrain all three Ms to be equal. Notice that this is not necessary for Type I fisheries, since M does not appear in the expressions for the us, and so all of the Fs and Ms are separable. This additional constraint also usually provides better precision. Accepting a constant natural mortality rate, we can now estimate F_{1i}, F_{2i} (i = 1, 2, 3), and M. We used a reporting rate of 0.5 in this example for both of the user groups. Estimates for this model are found in Table 4.

It was possible to estimate variances for the interaction coefficients from a single data set in the following way: (*i*) we ran SURVIV with "proc estimate" to get estimates of Fs and M, (*ii*) we then reran SURVIV with "proc simulate" and initialized all of the parameters in the model by the estimated values from step *i*, and (*iii*) we used SAS (SAS Institute Inc. 1989) "proc means" to calculate the interaction coefficients and the variance of the interaction coefficients.

Since fishery 1 had higher annual Fs, it was able to pick up a greater proportion of fishery 2's catch (~19%) whereas fishery 2 was only able to pick up about 4% of the catch if fishery 1 was closed.

In practice, data pertaining to reporting rate (as obtained from a variable-reward study, planted tags, or a port sampling program) can be included in the likelihood for the recapture matrix so that the reporting rate and mortality rates are estimated simultaneously (see Hoenig et al. 1998*a*).

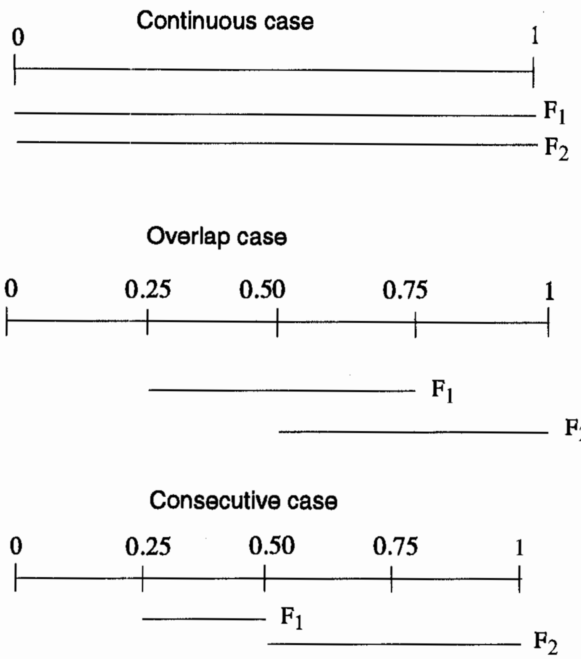
Simulation study

Simulation methods

We performed a simulation study to explore the precision of parameters in our models and dynamics of the coefficients of interaction under different fishing scenarios. Three possible scenarios for fisheries operation were considered in these simulations: a continuous case, an overlap case, and a consecutive case (see Fig. 3). In the continuous case, both fisheries were assumed to be in operation for the entire year (where the time interval is 0–1 for the whole year). For the overlap case, fishery 1 operated from time t_1 = 0.25 to t_3 = 0.75, while fishery 2 operated from time t_2 = 0.50 to time t_4 = 1.0. Thus, there was overlap for 0.25 of the year. Finally, in the consecutive case, fishery 1 operated from time t_1 = 0.25 to time t_2 = 0.5 and fishery 2 operated from time t_3 = 0.5 to t_4 = 1.0.

In all three cases, we allowed the Fs to take the values 0.1, 0.2, or 0.3 per year and the Ms could be 0.2 or 0.4 per year. For scenarios where the fishery operated for less than 1 year, the product of $F\Delta t$ (where Δt is the fraction of the year fished) was set to the above values. Hence, a fishery that operated for half the year fished with F = 0.6 for that amount of time, which is analogous to a continuous fishery with F =

Fig. 3. Fishery scenarios considered for each simulation study. The two user groups (1 and 2) have fishing mortalities F_1 and F_2, and the length of the bars represents the time of their respective operation.



0.3. This adjustment was done so that expected tag returns would be comparable, therefore making comparisons in precision more equitable. The size of the cohorts (number tagged each year) was either 500 or 1000, and the reporting rate was fixed at $\lambda = 0.8$ or 0.5. We estimated the parameters using proc simulate and proc estimate in the program SURVIV (White 1983) with 1000 simulations for each case.

In each simulation, we estimated a full and a reduced model. In the full model, F_{1i} and F_{2i} (i = 1, 2, 3) were allowed to vary between years, but the Ms were constrained ($M_1 = M_2 = M_3$). In the reduced model, we constrained the Fs and the Ms ($F_{11} = F_{12} = F_{13}$, $F_{21} = F_{22} = F_{23}$, and $M_1 = M_2 = M_3$). It was necessary to constrain the Ms to be able to estimate F_3. Without constraining the Ms, we can only estimate u_{13} and u_{23} for the third year.

Altogether, we had 72 different runs (3 × 2 × 2 × 2 different parameter combinations for three different fishery scenarios). Sample output is given in Table 5, where we compare the estimates and proportional standard errors, or coefficients of variation (CV), between the three scenarios.

Table 5. Sample output from 1000 simulations.

Parameter	Continuous	Overlap	Consecutive
Full model			
F_{11}	0.1021 (13%)	0.2020 (11%)	0.4038 (9%)
F_{12}	0.0977 (11%)	0.2002 (12%)	0.3998 (9%)
F_{13}	0.0982 (11%)	0.2015 (13%)	0.4029 (10%)
F_{21}	0.2961 (7%)	0.5926 (7%)	0.5925 (8%)
F_{22}	0.2950 (6%)	0.5924 (8%)	0.5928 (8%)
F_{23}	0.2954 (7%)	0.5968 (9%)	0.5964 (9%)
M	0.2053 (17%)	0.2093 (17%)	0.2089 (16%)
IC 1 on 2	0.3461 (3%)	0.4019 (4%)	0.4050 (4%)
IC 2 on 1	0.1382 (6%)	0.1133 (7%)	0.1032 (7%)
Reduced model			
F_{1i}	0.0991 (7%)	0.2009 (8%)	0.4014 (6%)
F_{2i}	0.2959 (5%)	0.5926 (5%)	0.5925 (5%)
M	0.2071 (15%)	0.2078 (14%)	0.2074 (13%)

Note: Estimates of mean of parameters (with CV in parentheses) are compared for the three scenarios, continuous, overlap, and consecutive, for full and reduced models. Results presented are for the case where N = 1000, λ = 0.8, and F_{1i} (or $F_{1i}\Delta t$) was initialized at 0.1, F_{2i} (or $F_{2i}\Delta t$) was initialized at 0.3, and M was initialized at 0.2.

Simulation results

Within each of the three fishing scenarios, there were consistent patterns between the CVs of the parameters. We found that CV(F = 0.1) > CV(F = 0.2) > CV(F = 0.3) and also that CV(M = 0.2) > CV(M = 0.4). Holding the Fs constant and increasing M caused the standard error on the Fs to increase. This was true for both the full and reduced models. In general, increasing the size of the cohort (from N = 500 to N = 1000) led to greater precision for the parameter estimates, as did increasing the reporting rate (from λ = 0.5 to λ = 0.8). More precision was gained from increasing the number of tagged fish than from increasing the reporting rate.

Comparing the estimates between the three fishing scenarios, we found the precisions to be very close, with no scenario consistently having the lowest CVs. For the "best" case, where N and λ were highest (N = 1000 and λ = 0.8), the CVs between scenarios only differed by at most 3%. For the "worst" cases, where N and λ were lowest, the difference in CVs was about 10%. The range of CVs for best cases was around 10% for Fs and 10–20% for M, while for the worst cases, CVs were 10–25% for Fs and 15–32% for M. The reduced cases (where both F and M were constant for all three years) were more precise than the full cases. Bias was negligible for all parameters in the simulations.

The coefficients of interaction were also calculated for each simulation run (see Table 5). Overall, the interaction coefficients were more precise than the estimates of F and M and were also unbiased. The precision only changed by about 3% between the best and worst cases. There was a large difference in the coefficients when the fisheries operated at different times of the year, as in the overlap and consecutive scenarios. The fishery operating first during a given year always saw a smaller gain when the second fishery, which fished later in the year, was closed. For the consecutive case, this gain ranged from 10 to 27%, and in the overlap case the gain ranged from 10 to 30%. When the first fishery was closed, the remaining fishery in these scenarios saw a much greater gain in catch, depending on its own level of effort. In both the consecutive and overlap cases, the second fishery could realize a gain of 14–40%. These "gains" should be interpreted as the proportion of the closed fishery's catch that could potentially be caught by the remaining fishery. The higher the F of the remaining fishery, the more it will catch per unit lost by the closed fishery.

A second type of interaction coefficient could be defined that would measure the proportional change in the catch of the remaining fishery, $(C_2^* - C_2)/C_2$, i.e., this coefficient would inform a fishery as to how much its catch would increase in proportion to what its own total catch was when both fisheries were in operation. For the consecutive case, this coefficient ranged from 6 to 24% for the first fishery and from 17 to 68% for the second fishery, while in the overlap case the range was from 7 to 28% for the first fishery and from 16 to 61% for the second fishery. A fishery with a low F could realize a greater proportional increase in its own total catch than a fishery with a higher F.

In the continuous case, where both fisheries operated all year long, a fishery could expect to take up 12–35% of its competitor's catch. Alternatively, this would translate into increasing its own total catch by about 11–43%.

If M was increased from 0.2 to 0.4, the interaction coefficients decreased. This is because fish foregone by the closed fishery would be likely to die as a result of natural mortality before they could be caught by the remaining fishery.

Discussion

By allowing that a fishery can be in operation for any amount of time, rather than lumping into the categories of pulse or continuous, we can calculate coefficients of interaction that more accurately reflect the potential gains in catch. The timing of the fisheries is very important in determining fishing mortalities and interaction coefficients. In particular, the order in which the fisheries operate regulates the extent of the effect seen when one fishery is closed.

The coefficient of interaction, as defined in eq. 1, represents the proportion of the catch foregone by the closed fishery that will be taken up by the remaining one. This estimate could be useful to management, in terms of setting and reevaluating catch limits and season lengths. A second coefficient of interaction can be defined as $(C_2^* - C_2)/C_2$, which is an estimate of the percentage increase that a particular fishery would see. This would be of more direct interest to fisheries in terms of planning and economic strategy, as it would allow a better "guess" at manpower, gear, and vessels that would be needed should a competing fishery be closed down.

For the simulation results, based on our choices for parameters, the values of the interaction coefficients are not high, but they are estimated in terms of the number of fish caught and the closure is considered for only the duration of the tagging experiment, which was 3 years. The values will be higher for longer closures. They will also be higher if biomass is taken into account because fish forgone will be heavier (sometimes much heavier) when recaptured later by the remaining fishery, which could be a topic of further investigation. This approach would be suitable for assessing interactions where differences between users relate to differences in selectivity. For example, one fishery might catch mainly 1-year-old fish and the other fishery mainly 3-year-old fish from the same year-class. In such a situation, management might close the fishery on 1-year-olds if recruitment overfishing was a concern.

The general formulas presented were demonstrated for two user groups, although they can clearly be applied to any number of user groups and thus can be used when data on a multiple user fishery are available, provided the tag returns are recorded separately and an independent estimate of reporting rate is available for each user group (from a creel survey, port sample, reward tagging, etc.).

We have investigated some aspects of interactions among multiple-user fisheries, thus illustrating how analyses of data from a properly designed and implemented tagging experiment can be used to assess and manage such fisheries.

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