CSIRO
MARINE RESEARCH

EXPLORING THE TRADE-OFF BETWEEN TAG RELEASES AND OBSERVER COVERAGE IN THE ESTIMATION OF MORTALITY RATES THROUGH AN INTEGRATED BROWNIE AND PETERSON MARK-RECAPTURE ESTIMATION APPROACH

Tom Polacheck
J. Paige Eveson
Geoff M. Laslett

Prepared for the CCSBT 4th Stock Assessment Group Meeting
25-29 August 2003, Christchurch, New Zealand

CCSBT-ESC/0309/22

TABLE OF CONTENTS

Abstract

A comprehensive framework for estimating data from multi-year tagging experiments in a fishery context is presented which demonstrates the need and value of integrating catch information into the estimation framework. Incorporation of the catch data not only allows for improved estimation of mortality rates (especially fishing mortality rates) but also allows for direct estimation of population size at the time of tagging. Having an approach for directly estimating these parameters independent of CPUE or fishery independent surveys provides a potentially powerful alternative for augmenting traditional stock assessment methods. In addition, the framework developed here allows for uncertainty in the catch data to be explicitly accounted for when reporting rates are estimated using observer data, as is likely to be the case for a number of fisheries (particularly pelagic longline fisheries). Simulation results are presented that demonstrate the value of directly incorporating the catch at age data into the estimation procedure and which illustrate the trade-off between levels of observer coverage and number of releases.

The CCSBT is currently undertaking a large scale multi-year, multi-cohort tagging experiment (Anon 2001a) as part of its collaborative Scientific Research Program (SRP) with the estimation of reporting rates from the longline fisheries to be based on observer data. The Scientific Committee recognized that "the appropriate level of observer coverage for estimation of tag returns" still needed to be resolved and that simulation studies addressing this issue were needed. Simulation results presented in this paper suggest that observer levels of 20-30% (or even greater) may be required to achieve reasonable levels of precision in the parameter estimates. The tagging program has now completed two years of tag releases and is preparing for a third year. Substantial numbers of these fish should now be vulnerable to exploitation by various longline fleets. No conclusion has been reached on levels of observer coverage with respect to the tagging program, and observer coverage to date has generally been minimal (<5%) (Anon. 2002). The results presented here indicate that unless appropriate levels of observer coverage are established and actually implemented now, it is highly unlikely that the tagging program will be able to meet its primary objective of being able to estimate mortality rates with sufficient levels of precision to substantially improve the SBT stock assessment.

Introduction

Natural and fishing mortality rates are critical components of the stock assessment process and their estimated values can be a major source of uncertainty in the resulting management advice. The estimates of these rates are also critical for improving our general understanding of the population dynamics of fish populations as they form a key component in evaluating the productivity and density dependent responses of a population. However, the direct estimation of fishing and mortality rates has generally been a relatively intractable problem in marine fish populations. Most assessment methods assume that natural mortality is known and is constant with age and time. The parameter values used in many assessments come from rather *ad hoc* approaches (e.g. catch curve, life history characteristics, analogy from other stocks). Similarly, the most common approach for estimating fishing mortality rates (e.g. VPA and related catch at age approaches) are dependent upon assumptions about selectivity and require auxiliary relative abundance indices. In recent years, the application of multi-year tagging experiments for estimating mortality rates using general models (Brownie et al. 1985) has been recognized as a powerful approach that can be applied in fishery situations to provide direct estimates of both natural and fishing mortality rates (e.g. Pollock et al. 1991; Polacheck et al. 1996, 1997). A number of papers have also further developed these models for application in particular fishery situations (Hoenig et al. 1998a,b; Hearn et al. 1999; Pollock et al. 2001). In addition, estimates of mortality rates from multi-year tagging programs using a Brownie framework have been incorporated into stock assessments and the approach underlies the design of a large scale- international tagging program for southern bluefin tuna (SBT) currently in progress (Anon. 2001a, Anon. 200b, Anon. 2002).

Brownie models for multi-year tagging data provide estimates of mortality rates from comparison of the return rates over time from the multiple releases. The power of the approach is that only data on the number of releases and returns (usually by cohort) are required to estimate overall mortality rates. In addition, fishing mortality can be separated from natural mortality rates if estimates of reporting rates are available.

Historically, the most common approaches for analysing single mark/recapture data were based on a Peterson type model (e.g. Seber 1973). In this case, the primary quantity being estimated is the population size at the beginning of the experiment. Population size is estimated based on the ratio of the observed number of tags returned within samples taken from the population given the known number of tags released into the population. The Peterson approach has not been widely used in large commercial fisheries because the size of the sample actually examined for tags is difficult to ascertain. However, along with estimates of mortality rates, knowledge of the actual population size is the other key piece of information needed in stock assessments and understanding population dynamics. In many fisheries, estimates of total removals (by age) are available. These estimates can take on the role of providing estimates of the sample sizes observed for tags in a Petersen type approach. However, this requires that the sample sizes are treated as random variables (as opposed to fixed, known values) and that this additional variability is incorporated into estimation if realistic estimates are to be achieved. There appears to be little work on Peterson type models in which the samples observed for recaptures is not known precisely but is also an estimated quantity. This appears to be because the approach is generally conceived as being applied in well controlled, experimental situations.

In the current paper, we develop tag-recapture models that combine catch data with data from multi-year tagging experiments to provide estimates of natural and fishing mortality rates as well as an estimate of abundance. We do this by extending the basic Brownie model to incorporate catch at age data. We initially explore this model for the situation where reporting rates are known and explore the trade-off between the relative precision in the tagging data (e.g. the number of releases) and in the catch-at-age data. We then extend the model to the situation in which reporting rates are estimated from observer data from a portion of the fleet. This allows us to look at how the relative trade-off between effort put into tagging and observers affects the overall mortality and abundance estimates.

Basic Dynamic Model

The basic model underlying the analyses of the multi-year tagging experiments used here is the general population dynamic equations commonly used in fisheries. These equations involve exponential and competing natural and fishing mortality rates. Thus for a cohort of animals of a given age, the number that survive is

$$P_{i,t+1} = P_{i,t}\exp\{-F_{i,t} - M_{i,t}\} \tag{1}$$

$$C_{i,t} = \frac{F_{i,t}}{F_{i,t} + M_{i,t}} P_{i,t}\left(1 - \exp\{-F_{i,t} - M_{i,t}\}\right) \tag{2}$$

where:

$P_{i,t}$ = the number of individuals of age i at time t
$C_{i,t}$ = the catch of individuals of age i at time t
$F_{i,t}$ = the instantaneous fishing mortality rate for individuals of age i at time t
$M_{i,t}$ = the instantaneous natural mortality rate for individuals of age i at time t.

In most fisheries contexts, $M_{i,t}$ will be assumed to be constant with time, although multi-year and multi-cohort tagging programs can provide year and age specific natural mortality rates. In the current paper, we focus on multi-year tagging experiment involving a single cohort. As such, we will drop the t subscript and express everything in terms of age.

In the context of a tagging experiment, the above equations provide the basis for predicting the expected number of returns assuming that the tag fish constitute a representative sample of the population. Following Brownie et al. (1985), the expected number of tags recaptured and returned from a particular cohort at age i from releases at age a ($R_{a,i}$) can be expressed as:

Table 1.

Release	#	Expected # returns from age class i				
Age	Releases	1	2	3	4	5
1	N_1	$\lambda_1 N_1 f_1$	$\lambda_2 N_1 S_1 f_2$	$\lambda_3 N_1 S_1 S_2 f_3$	$\lambda_4 N_1 S_1 S_2 S_3 f_4$	$\lambda_5 N_1 S_1 S_2 S_3 S_4 f_5$
2	N_2		$\lambda_2 N_2 f_2$	$\lambda_3 N_2 S_2 f_3$	$\lambda_4 N_2 S_2 S_3 f_4$	$\lambda_5 N_2 S_2 S_3 S_4 f_5$
3	N_3			$\lambda_3 N_3 f_3$	$\lambda_4 N_3 S_3 f_4$	$\lambda_5 N_3 S_3 S_4 f_5$

Where:

N_a= the number of tag releases of age a fish from a specific cohort
$f_i = (1 - \exp\{-M_i - F_i\})F_i/(M_i + F_i)$, and
$S_i = \exp\{-M_i - F_i\}$
λ_i= tag reporting rate for fish captured at age i.

The above expressions for the expected number of returns assume complete and instantaneous mixing of tagged fish and no tagging mortality or loss. These issues are discussed further below – essentially, if the assumptions are not met, additional parameters and potentially additional data will need to be introduced to account for these factors.

Equations (1) and (2) can also be used to provide analogous expressions for the expected catches of fish. The expected catches of age *i* fish from a particular cohort, conditional on the size of the cohort at age 1 (P_1). Thus,

Table 2.

Size of cohort	Expected catch from age class i 1	2	3	4	5
P_1	$P_1 f_1$	$P_1 S_1 f_2$	$P_1 S_1 S_2 f_3$	$P_1 S_1 S_2 S_3 f_4$	$P_1 S_1 S_2 S_3 S_4 f_5$

Essentially, the catch data can be viewed as a tagging experiment in which the number of releases (P_1) is unknown and is a parameter to be estimated. However, unlike a tagging experiment where little uncertainty exists about the number of returns[1], the actual catch at age information will be an estimated quantity usually derived from a multi-stage sampling of catches for length combined with age/length keys derived from otoliths. Because P_1 is unknown, it is not possible from the catch at age data alone to derive estimates of the mortality rates[2]. However, combining the catch at age data with the multi-year tagging data allows P_1 to be estimated and additional information on F and M contained in the catch data to be extracted.

Estimation Model Assuming 100% Reporting Rates

We first explore the situation in which the reporting rates are assumed to be 100%. While in most situations this is likely to be an unrealistic assumption, this situation provides a straightforward way to examine the potential gain achieved by combining the tagging and catch at age data. We use a maximum likelihood approach for the estimation of the unknown *F*, *M* and *P* parameters. As developed in Brownie et al. (1985), if each tag recapture is assumed to be independent, then the numbers of returns at age (including those not returned) from any individual release are expected to be multinomial, and the likelihood function for the observed numbers of returns from all release events is the product of multinomials:

$$L_R = \prod_a \left(\frac{N_a!}{\prod_{i \geq a} R_{a,i}!\,(N_a - R_{a,\bullet})!} \prod_{i \geq a} p_{a,i}^{R_{a,i}} (1 - p_{a,\bullet})^{N_a - R_{a,\bullet}} \right) \tag{3}$$

where a indexes release age, i indexes recapture age, and $p_{a,i}$ is the probability of a tag being returned from an age i fish released at age a. An expression for $p_{a,i}$ can be

[1] Minor uncertainties may exist in the number of return because some tags may be returned with missing data (e.g. the tag numbers may have become unreadable or the date of recapture may be missing).
[2] Even if *M* is assumed known as in many stock assessments, there are still too many parameters and this is the reason that catch at age stock assessment models require additional sources of data for “tuning” (See Hilborn and Walters 1992).

obtained from the expected number of returns in Table 1 by dividing by N_i. Explicitly,

$$p_{a,i} = \begin{cases} \lambda_i f_i & i = a \\ \lambda_i S_a \cdots S_{i-1} f_i & i > a \end{cases}$$

Note that in equation (3) and in subsequent equations, a dot in the subscript denotes summation over the index it replaces.

Similarly, if we assume that all fish in a cohort are independent, then we can think of the catch at age data (including those fish not caught) as random multinomial, where each fish has a probability of being captured at age *i* or not captured. Expressions for the catch probabilities can be obtained by dividing the expected catches in Table 2 by the initial cohort size (P_1).

To this point we have been assuming that the numbers of fish caught at each age are known accurately; however, the age distribution of the catch is usually determined by taking a sample of the catch, estimating the ages of fish in the sample (either from lengths or from direct aging of hard parts), and then scaling up the estimated age frequencies of the sample by the ratio of the catch size to the sample size. We have chosen to represent the error in the catch at age data that results from this estimation procedure as Gaussian with a common coefficient of variation (CV), υ, across all age classes. To fit a model with both multinomial "process" error and Gaussian sampling/measurement error would require a relatively sophisticated approach, such as a Kalman filter. However, in most fisheries the number of fish in the cohort from which catches are being taken will be very large such that the multinomial error will be negligible compared to the Gaussian sampling error. In such cases, only the latter needs to be considered. Thus, the likelihood for the catch at age data can be expressed as

$$L_C = \prod_i \frac{1}{\sqrt{2\pi}\sigma_i} \exp\left(-\frac{1}{2}\left(\frac{C_i - E(C_i)}{\sigma_i} \right)^2 \right) \tag{4}$$

where the expected catch at age *i*, $E(C_i)$, is given in Table 2 and $\sigma_i = \upsilon E(C_i)$.

The overall likelihood for the combined recapture and catch data can be obtained by multiplying likelihoods (3) and (4) together:

$$L = L_R \times L_C \tag{5}$$

Estimates of the *F*, *M* and *P* parameters can be obtained by maximizing the likelihood in (5) (or, equivalently, by minimizing the negative log of this likelihood). The parameter υ cannot be estimated from the data when a separate *F* is estimated for each year of recapture, thus we assume that it is known.

The information for estimating M_i comes from the differential between the expected returns at age $i+1$ of fish released at age *i* and those released at age $i+1$. Thus, in an experiment with *n* release events, estimates can only be obtained for M_i to M_{n-1} because subsequent *M*'s are not separable from the corresponding *F* parameters. In an experiment with three release events, as illustrated in Table1, only M_1 and M_2 are estimable. Therefore we assume that $M_i = M_{n-1}$ for $i \geq n$.

Simulation Results Assuming 100% Reporting Rates

Value of incorporating catch data

To investigate the value of incorporating catch at age data in terms of the accuracy of the parameter estimates, we simulated multinomial tag-recapture data and Gaussian catch data. We then compared the parameter estimates obtained using just the tag-recapture data with those obtained using both the tagging data and the catch data.

We generated tagging data for three consecutive release years (tagging the same cohort each year) and five recapture years using the following values:

$$\begin{aligned} N_a &= 1000 \quad a = 1,\ldots,3 \\ F_i &= 0.15 \quad i = 1,\ldots,5 \\ M_i &= 0.2 \quad i = 1,\ldots,5 \end{aligned}$$

Gaussian catch data were generated using the same F and M values, an initial population size of $P_1 = 100000$, and a range of CV's (υ = 0.05, 0.1, 0.2, and 0.5).

Although we used constant mortalities across ages to generate the data, in our model we estimate a separate fishing mortality for each age (F_i, $i = 1,\ldots,5$), a natural mortality for age 1 (M_1), and a natural mortality for age 2 and above (M_2) (since this is the most we can estimate with three release years). When we incorporate the catch data into the likelihood, we also get a direct estimate of the initial size of the cohort P_1. If the tagging data alone are used to estimate the mortality rate parameters, the catch data can be used subsequently to obtain an estimate of P_1; in fact, an estimate of P_1 is generated for each age of recapture by setting the expected catch at age (as given in Table 2) equal to the observed catch at age, plugging in the maximum likelihood estimates of the F's and M's, and solving for P_1. Which of these estimates should be most accurate is not obvious.

We generated 100 tag-recapture data sets, and for each value of υ we generated 100 catch data sets. Parameter estimates were obtained first using just the tagging data to maximize likelihood (3) and second using the combined tagging and catch data to maximize likelihood (5). As we would expect, the parameter estimates were unbiased regardless of whether the catch data were included and regardless of the value of υ; however, the precision of the estimates varied. Figure 1a shows that including the catch data improved of the mortality rate estimates (i.e. decreased their coefficient of variation), with the greatest improvement in the estimates of F_1, F_2, and M_1. The improvement lessened as the CV of the catch increased, with almost no gain for $\upsilon \geq 0.2$. For the initial population size parameter, the maximum likelihood estimate of P_1 obtained directly from the combined tagging and catch likelihood was more precise than any of the estimates obtained by substituting the tagging data mortality rate estimates into the expected catch equations (Figure 1b). This was true for all values of υ, and the relative decrease in the coefficient of variation from including the catch data was about twice regardless of the catch variability.

Trade-off between number of releases and accuracy of catch data

We have established that incorporating the catch data improves the precision of the parameter estimates, and that the degree of improvement depends on the amount of variability in the catch data (at least for the mortality rate estimates). Presumably, increasing the number of tag releases will also result in more precise parameter estimates. For designing a tagging experiment, it would be very useful to know whether resources would be better spent on tagging large numbers of fish or on reducing the uncertainty in the catch at age data (through more port sampling, more on-board observers, collection of otoliths, et cetera).

To address this question, we carried out simulations in which we varied the number of releases (N) from 100 to 2000 and the catch CV (υ) from 0.025 to 0.5. For each combination of N and υ, we generated 100 simulated data sets and estimated the mortality rate parameters and initial population size by maximizing the joint tagging and catch likelihood. In generating the data, we again assumed three consecutive release years with an equal number of releases in each year, five recapture years, and the same values of F, M and P as before.

The results are summarized in Figure 2a-h. First concentrate on the estimates of the fishing mortality rates (Figure 2a-e). Increasing the number of releases resulted in exponential decreases in the CV of all the fishing mortality rate estimates (F_1 to F_5), with the rate of decrease slowing considerably after about 1000 releases. Reducing the variability in the catch data also reduced the CV of the fishing mortality rate estimates, however the response lessened as the age of the fish increased such that by age 5, the CV of the F_5 estimates was essentially unaffected by the variability in the catch data. For F_1 and F_2, there is also a clear interaction between the number of releases and the variability of the catch. In particular, for small numbers of releases (<1000), the gain from tagging more fish is greatest when the catch CV is large (i.e. if the catch data is not very informative, then a lot is gained from having more tag releases). This interaction diminishes with age, and is barely discernable by age 5.

With regard to the population size estimate, P_1, the number of releases had relatively little effect on its precision (Figure 2f). This is not surprising since the tagging data only influences the estimation of P_1 indirectly through its influence on the mortality rate estimates. On the contrary, the variability in the catch data had a large influence on the precision of the P_1 estimate. Decreasing the variability in the catch data resulted in a linear decrease in the CV of P_1 over the complete range of catch CV's considered.

Similar to the fishing mortality estimates, there were exponential decreases in the CV's of the natural mortality rate estimates, M_1 and M_2, as the number of releases increased (Figure 2g-h). There was little response to changes in the CV of the catch.

Estimation Model with Reporting Rates Estimated From Observer Data

When recapture information comes from commercial fisheries, we do not expect the reporting rates to be 100% nor do we expect them to be known; thus, they must be estimated. Although tagging data contain information about reporting rates, the information is generally weak and insufficient to distinguish non-reporting from natural mortality and fishing mortality without making some fairly restrictive assumptions (see Hoenig et al. 1998a). Auxiliary data for estimating reporting rates can be obtained through a variety of methods, one of which involves having observers monitor the catches from a portion of the fishery. In this situation, it is assumed that in the portion of the fishery with observers, all recaptured tags are reported (i.e. the reporting rate is 100% for all age classes), whereas in the portion of the fishery without observers the reporting rate for age *i* fish is λ_i.

We split tag returns into those coming from the observed component of the fishery ($R^o_{a,i}$) and those coming from the unobserved component ($R^u_{a,i}$). Let δ_i denote the proportion of age *i* fish in the observed component, then the probability of a tag being returned from the observed component from an age *i* fish released at age *a* is

$$p^o_{a,i} = \begin{cases} \delta_i f_i & i = a \\ \delta_i S_a \cdots S_{i-1} f_i & i > a \end{cases} \tag{6}$$

Likewise, the probability of a tag being returned from the unobserved component from an age *i* fish released at age *a* is

$$p^u_{a,i} = \begin{cases} (1-\delta_i)\lambda_i f_i & i = a \\ (1-\delta_i)\lambda_i S_a \cdots S_{i-1} f_i & i > a \end{cases} \tag{7}$$

For any individual release, the numbers of returns at age from the observed component and from the unobserved component (as well as those not returned from either) are expected to be multinomial with probabilities given in (6) and (7). Thus, the likelihood equation for all the returns is:

$$L^*_R = \prod_a \left(\frac{N_a!}{\prod_{i \ge a} R^o_{a,i}!\, R^u_{a,i}!\, (N_a - R^o_{a,i} - R^u_{a,i})!} \prod_{i \ge a} {p^o_{a,i}}^{R^o_{a,i}} {p^u_{a,i}}^{R^u_{a,i}} \left(1 - p^o_{a,i} - p^u_{a,i}\right)^{N_a - R^o_{a,i} - R^u_{a,i}} \right) \tag{8}$$

Likewise, we split the total catches into those coming from the observed component of the fishery (C^o_i) and those coming from the unobserved component (C^u_i). We assumed the catches in the observed and unobserved components were Gaussian with CV υ. Recall that δ_i denotes the proportion of age *i* fish in the observed component. Thus, the likelihood for all the catch is:

$$L^*_C = \prod_i \frac{1}{2\pi\sigma_i^2} \exp\left(-\frac{1}{2\sigma_i^2} \left\{ \left(C^o_i - \delta_i E(C_i)\right)^2 + \left(C^u_i - (1-\delta_i) E(C_i)\right)^2 \right\} \right) \tag{9}$$

where $E(C_i)$ is given in Table 2 and $\sigma_i = \upsilon \delta_i E(C_i)$.

The overall likelihood for the combined recapture and catch data can be obtained by multiplying likelihoods (8) and (9) together:

$$L^* = L^*_R \times L^*_C \tag{10}$$

We now obtain estimates of the δ and λ parameters in addition to the *F*, *M* and *P* parameters by maximizing the likelihood in (10). Again, the parameter υ cannot be estimated from the data when a separate F is estimated for each year of recapture, thus we assume that it is known. It also still holds true that in an experiment with n release events, estimates can only be obtained for M_i to M_{n-1}.

Simulations Results with Reporting Rates Estimated From Observer Data

Trade-off between number of releases and observer coverage assuming direct relationship between observer coverage and accuracy of catch at age data

In the case where reporting rates are estimated from observer information, we can look at the trade-off between increasing the number of releases and increasing the level of observer coverage on the precision of the parameter estimates. Increasing observer coverage will improve the parameter estimates through improving the reporting rate estimates and also, we assume here, by improving the accuracy of the catch at age data (since observers take length measurements on all fish). A hypothetical relationship between the level of observer coverage (α) and the CV of the catch data (υ) which we believe to be reasonable approximation for exploring the trade-off is proposed in Figure 3. The formula used to generate this curve is

$$\upsilon = 0.75 * (.05)^{\sqrt{\alpha}} \tag{11}$$

Note that even with 100% observer coverage, the CV of the catch does not go to zero in equation (11). This is because even with 100% sampling for lengths, uncertainties in the catch at age estimates will still exist due to the sampling and uncertainties involved in direct aging.

We carried out simulations in which we varied the number of releases (N) from 100 to 2000 and the level of observer coverage (α) from 0.05 to 0.9. For each combination of N and α, we generated 100 simulated data sets and estimated the F, M, P, δ and λ parameters by maximizing the joint tagging and catch likelihood in (10). To generate the data, we assumed the same design as in our simulations for the case of 100% reporting rates. Specifically, we assumed three consecutive release years with an equal number of releases in each year and five recapture years. We also used the same parameter values, namely $F_i = 0.15$ and $M_i = 0.2$ for all ages i, and P_1 =100000. We assumed the reporting rate in the unobserved component to be 0.75 for all ages (i.e. $\lambda_i = 0.75$ for all i) , and the proportion of age i fish in the unobserved component to be the level of observer coverage, α, for all ages (i.e. $\delta_i = \alpha$ for all i). The coefficient of variation used to generate the catch data depended on the level of observer coverage, and was calculated using equation (11).

Recall that in maximizing the likelihood, the coefficient of variation of the catch is assumed known and that natural mortality is assumed to be the same for ages 2 and above.

The results for the parameters of interest are summarized in Figure 4a-h. First concentrate on the fishing mortality rate results (Figure 4a-e). Increasing the number of releases had almost no effect on the CV of the fishing mortality rate estimate at age 1. As age increased, the precision in the fishing mortality rate estimate started to improve when the number of releases was increased. This makes sense because if the number of tag releases is too small then there would be very few tag returns from older fish (since most of the tagged fish would have died earlier due to natural mortality or fishing). On the other hand, increasing the level of observer coverage improved the precision of the fishing mortality rate estimates at all ages, quite dramatically at age 1 and progressively less so as age increased. This is quite a different result than was obtained in the case with 100% reporting rates.

The results for the population size parameter, P_1, are similar to those for the F estimates in that increasing the level of observer coverage results in fairly substantial increases in the accuracy of the parameter estimate whereas increasing the number of releases has a lesser effect, especially after about 500 releases (Figure 4f).

As in the case of 100% reporting rates, there were exponential decreases in the CV's of the natural mortality rate estimates, M_1 and M_2, as the number of releases increased. There were also decreases in the CV's of these estimates as the level of observer coverage increased, although the response was not as great as for the F and P estimates (Figure 4g-h).

So far we have only commented on the patterns in the CV's for the parameter estimates. It should be noted that, as we would expect, the magnitude of the CV's is greater for all parameter estimates when the reporting rates must be estimated than when they are assumed to be 100%.

Trade-off between number of releases and observer coverage assuming independence between observer coverage and accuracy of catch at age data

In some situations, the accuracy of the catch at age data will not be determined by the level of observer coverage. For example, there may be a good port sampling program so that the catch at age data is well estimated even when the observer coverage is low. In such a case, increasing the level of observer coverage would only affect the accuracy of the parameter estimates through improving the accuracy of the reporting rate estimates. We also conducted simulations to investigate this situation, where everything was kept the same as in the previous simulations except we assumed the coefficient of variation in the catch (υ) to be 0.1 regardless of the level of observer coverage instead of using equation (11).

The results from these simulations are summarized in Figure 5a-h. Again we concentrate on the fishing mortality rate results first (Figure 5a-e). The patterns in the results are somewhat similar to those obtained in the case of 100% reporting rate in that increasing the number of releases resulted in exponential decreases in the CV of the F estimates (F_1 to F_5), with the rate of decrease slowing considerably after about 1000 releases. Increasing the level of observer coverage resulted in substantial reductions in the CV of the F estimates, and this was true even when the number of releases was large. The gains from increasing the level of observer coverage lessened with age, but could still be discerned in the F_5 estimates.

For the population size parameter, P_1, both increasing the level of observer coverage and increasing the number of releases reduces the CV of the parameter estimate, although the gains are not large for observer coverage greater than about 0.2 and tag releases beyond about 500 (Figure 5f).

Again there were exponential decreases in the CV's of the natural mortality rate estimates, M_1 and M_2, as the number of releases increased, but there was only a very small response to increases in the level of observer coverage (Figure 5g-h).

Discussion

The current paper has developed a comprehensive framework for estimating data from multi-year tagging experiments in a fishery context. In particular, the framework demonstrates the need and value of integrating data on the catches with an appropriate error structure into the estimation framework. Incorporation of the catch data not only allows for improved estimation of mortality rates (especially fishing mortality rates) but also allows for direct estimation of population size at the time of tagging. These quantities (abundance, natural mortality and rates of exploitation) are the primary quantities required to be estimated in stock assessments. Having an approach for directly estimating these independent of CPUE or fishery independent surveys provides a potentially powerful approach for augmenting traditional stock assessments.

In addition, the framework developed here allows for uncertainty in the catch data to be explicitly accounted for in the estimation of reporting rates when they are estimated using observer data, as is likely to be the case for a number of fisheries (particularly pelagic longline ones). Previous reporting rate estimators have been conditional on the catch at age data (i.e. they have assumed that the catches at age are known exactly without error) (e.g. Hearn et al. 1999; Polacheck et al. 1997; Polacheck and Hearn, in press). As has been shown here, ignoring error in the catch data is likely to substantially overestimate the precision in the resulting mortality rate and abundance estimates. Moreover, in a experimental design context, ignoring the uncertainty associated with the catch data will underestimate the relative value of observers in the consideration of the trade-off between number of releases and observer coverage. For example, Polacheck and Hearn (in press) found that there was nearly an equal trade-off in the precision of fishing mortality rate estimates between increased observer coverage and increased number of tag releases when reporting rates were being estimated from observer data and catches were assumed known without error[3]. The results in the current paper indicate that at lower levels of observer coverage there tends to be a much larger marginal improvement in estimates of fishing mortality rates (especially for younger ages) and of population size from increasing observer coverage than from increasing the number of tag releases (Figures 4 and 5). This is particularly true when the observer data are the primary source of information used to estimate the age composition of the catch (Figure 4).

The CCSBT is currently undertaking a large scale multi-year, multi-cohort tagging experiment (Anon 2001a) as part of its collaborative Scientific Research Program

[3] In this case, they were only considering an experiment involving a single release with M assumed known.

(SRP). One key element of the SRP is a scientific observer program (Anon 2001b). In initiating a scientific observer program, multiple objectives were identified. Obtaining sufficient data for estimating reporting rates was identified as one key component of the observer program. A 10% observer target level was agreed on by the CCSBT for catch and effort monitoring. However, it was recognized that “the appropriate level of observer coverage for estimation of tag returns will depend on the scale of the tagging program and the tag recovery rate” and will need to be determined in the planning stages of the tagging program (Anon 2001b). The CCSBT Tagging Program Workshop that developed the design for the current tagging program noted that the appropriate level of observer coverage still needed to be resolved and recognized the need for further simulation studies to help resolve this question (Anon. 2001a).

The development of the estimation framework and the simulation studies presented in this paper provide insights into the level of observer coverage that is likely to be required in large scale multi-year tagging programs, such as the one being conducted by the CCSBT. The results suggest that observer levels of at least 20-30% may be required to achieve reasonable levels of precision in the estimated parameters. Moreover, the results presented here are clearly optimistic as a number of factors are not included:

1. The actual variance in the number of recaptures is likely to be over-dispersed relative to a multinominal distribution (See Polacheck et al. 1997).
2. The variance of the observed number of tags returned is based on the overall proportion of the catch that is observed and does not take into account the multi-stage component of observer sampling. The actual variance would be expected to higher due to multi-stage sampling (see below).
3. The variance of the catch at age estimates is likely to be higher at low observer coverage levels due to the multi-stage component of observer sampling combined with potentially large over-dispersion in the capture process.
4. There is additional variance introduced by tag mortality and tag shedding.

These issues have been discussed elsewhere (e.g. Polacheck 2001; Polacheck and Hearn, in press) and, thus, will not be repeated here. However, it is noted that the CCSBT tagging program has now completed two years of tag releases and is preparing for a third year of releases beginning next December. Substantial numbers of these fish should now be vulnerable to exploitation by various longline fleets, yet no conclusion has been reached by the Scientific Committee on recommended levels of observer coverage required to meet the tagging objectives of the CCSBT SRP. Observer coverage to date has generally been minimal (<5%) (Anon. 2002). The results presented here indicate that unless appropriate levels of observer coverage are established and actually implemented now, it is highly unlikely that the tagging program will be able to meet its primary objective of being able to estimate mortality rates with sufficient levels of precision to substantially improve the SBT stock assessment.

Literature Cited

Anon. 2001a. Report of the tagging program workshop. Commission for the Conservation of Southern Bluefin Tuna. 2-4 October. Canberra, Australia.

Anon. 2001b. Report of the eighth annual meeting. Commission for the Conservation of Southern Bluefin Tuna. 15-19 October. Miyako, Japan.

Anon. 2002. Report of the seventh meeting of the scientific committee. Commission for the Conservation of Southern Bluefin Tuna. 9-11 2002. Canberra, Australia.

Brownie, C., D. R. Anderson, K. P. Burnham, and D. S. Robson, 1985. Statistical inference from band recovery data: a handbook. U.S. Fish and Wildlife Resource Publication 156.

Hearn, W. S., T. Polacheck, K. H. Pollock, and W. Whitelaw. 1999. Estimation of tag reporting rates in age-structured multicomponent fisheries where one component has observers. Canadian Journal of Fisheries and Aquatic Sciences **56**: 1255-1265.

Hilborn, R., and C. J. Walters. 1992. Quantitative fisheries stock assessment: choice, dynamics and uncertainty. Chapman and Hall, London. 570pp.

Hoenig, J. M., N. J. Barrowman, W. S. Hearn, and K. H. Pollock. 1998a. Multiyear tagging studies incorporating fishing effort data. Canadian Journal of Fisheries and Aquatic Sciences **55**: 1466-1476.

Hoenig, J. M., N. J. Barrowman, K. H. Pollock, E. N. Brooks, W. S. Hearn, and T. Polacheck. 1998b. Models for tagging data that allow for incomplete mixing of newly tagged animals. Canadian Journal of Fisheries and Aquatic Sciences **55**: 1477-1483.

Polacheck, T., W. Hearn, C. Millar, W. Whitelaw and C. Stanley. 1996. Estimation of natural and fishing mortality rates for juvenile southern bluefin tuna based on multi-year tagging of cohorts. CCSBT/SC/96/11.

Polacheck, T., W. Hearn, C. Millar, W. Whitelaw, and C. Stanley. 1997. Updated estimates of mortality rates for juvenile southern bluefin tuna from multi-year tagging of cohorts. CCSBT/SC/970726.

Polacheck, T., and A. Preece. 1998. Documentation of the virtual population methods and model inputs used for estimating current and historical stock sizes of southern bluefin tuna: updates and modifications 1998. CCSBT-SC/9807/37.

Polacheck, T. 2001. Effects of observer coverage in the estimation of reporting and fishing mortality rates in tagging experiments. CCSBT-SC/0103/19.

Polacheck, T., and W. Hearn. In press. Designing tagging programs for pelagic longline fisheries: trade-offs between the number of releases and observer coverage. N. Amer. J. Fisheries Management.

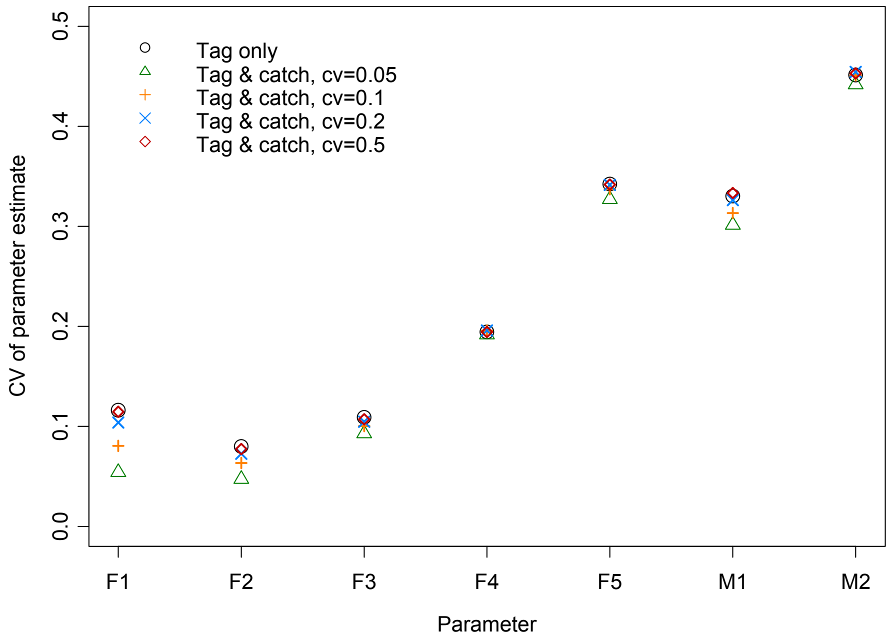
Pollock, K. H., J. M. Hoenig, and C. M. Jones. 1991. Estimation of fishing and natural mortality when a tagging study is combined with a creel survey or port sampling. Am. Fish Soc. Symp. **12**: 423-434.

Pollock, K. H., W. S. Hearn, and T. Polacheck. 2002. A general model for tagging on multiple component fisheries: an integration of age-dependent reporting rates and mortality estimation. Environmental and Ecological Statistics **9**: 57-69.

Seber, G. A. F. 1973. The estimation of animal abundance and related parameters. Charles Griffin, London. 506pp.

Figure 1. Improvement in the accuracy of a) mortality parameter estimates and b) initial population size estimate, by including catch data in addition to tagging data. Recapture data are assumed to be multinomial and catch data are assumed to be Gaussian with a range of coefficient of variations.

a)



b)

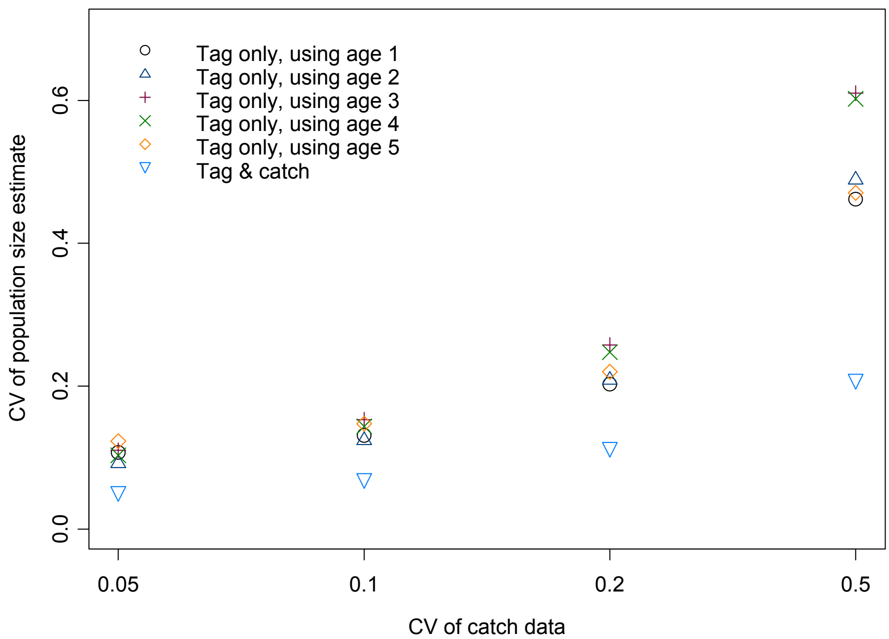
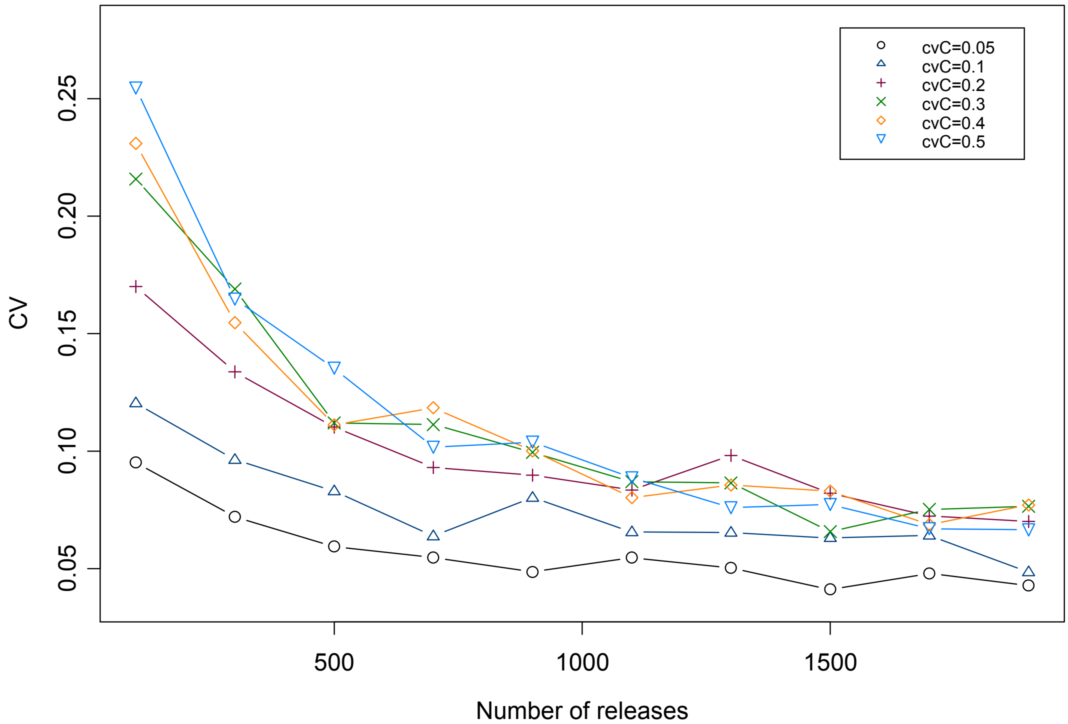


Figure 2. Effect of changing the number of releases and coefficient of variation in the catch (denoted by cvC) on the coefficient of variation of the fishing mortality rate estimates (a-e), the population size estimate (f), and the mortality rate estimates (g-h) when reporting rates are assumed to be 100%.

a) F_1



b) F_2

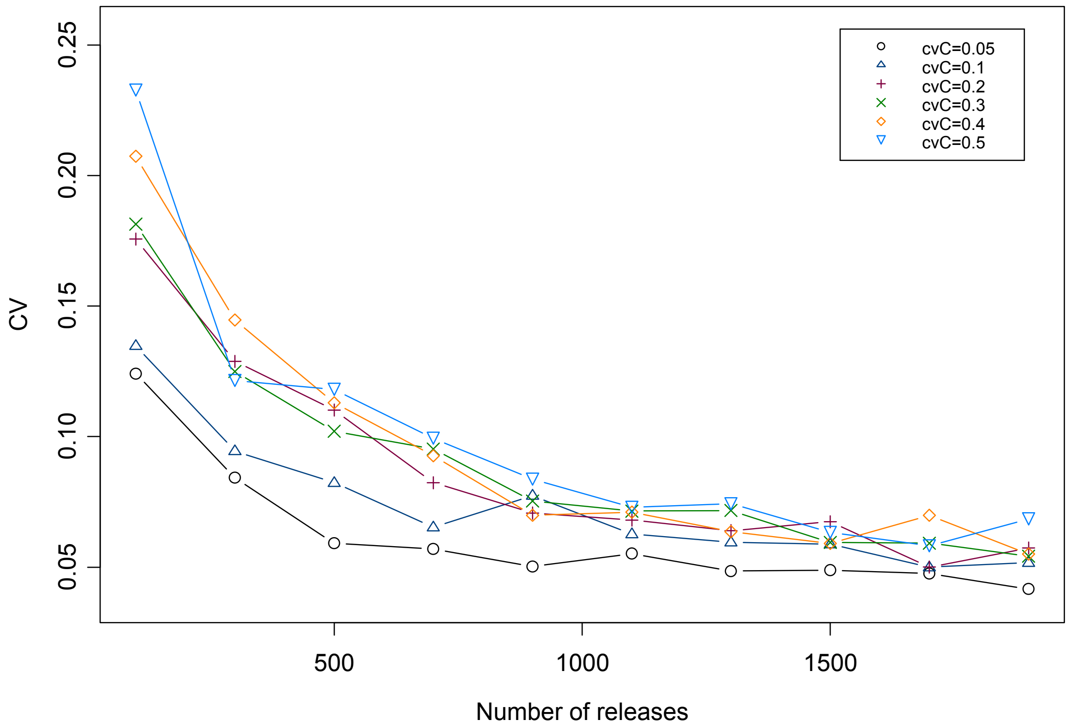
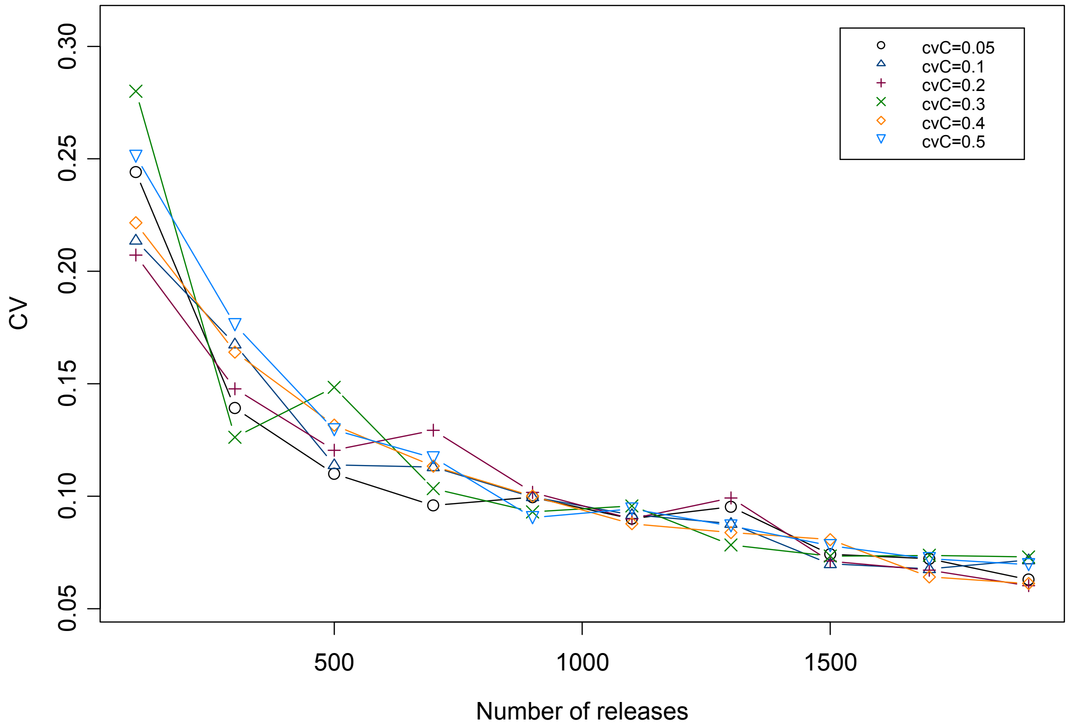


Figure 2 cont.

c) F_3



d) F_4

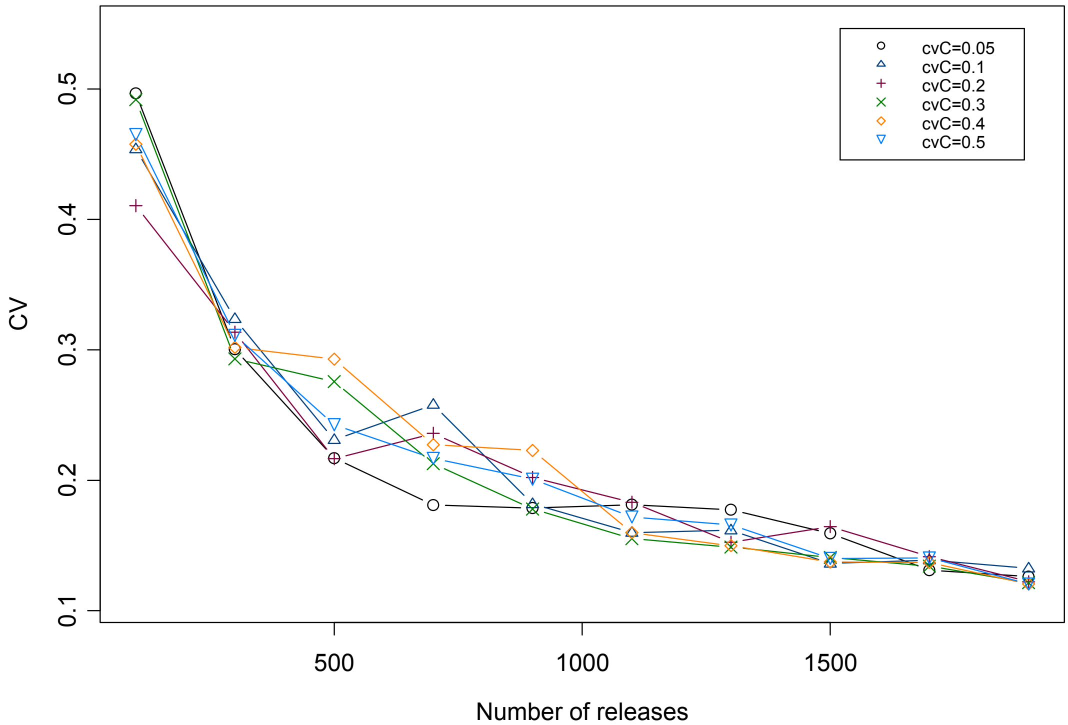
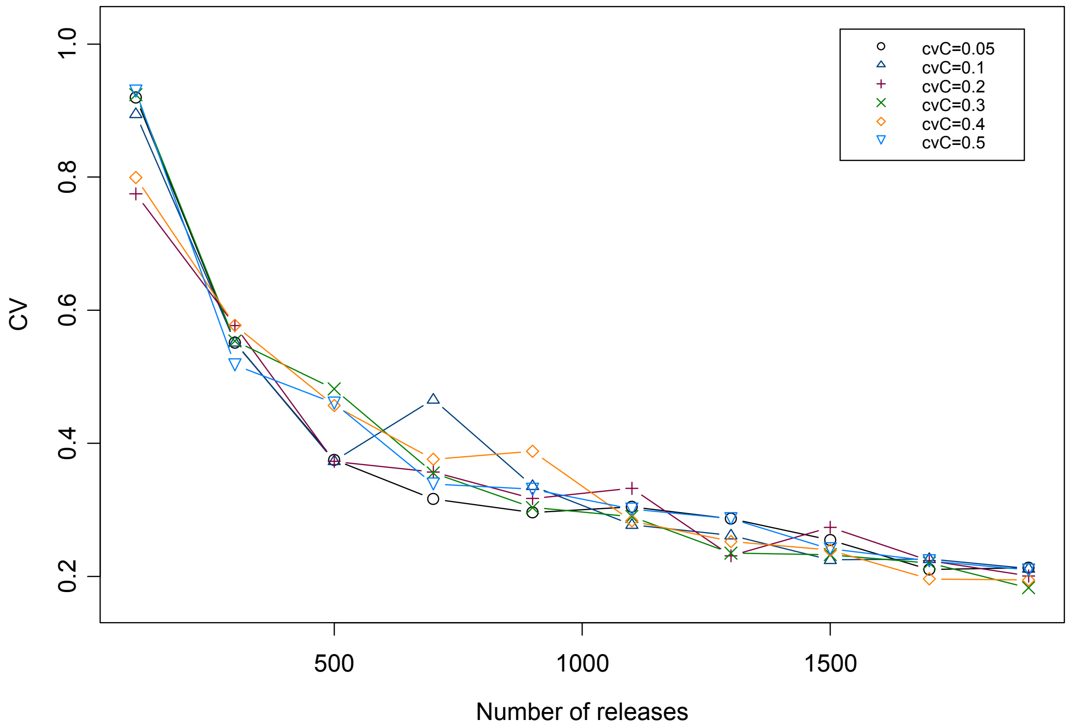


Figure 2 cont.

e) F_5



f) P_1

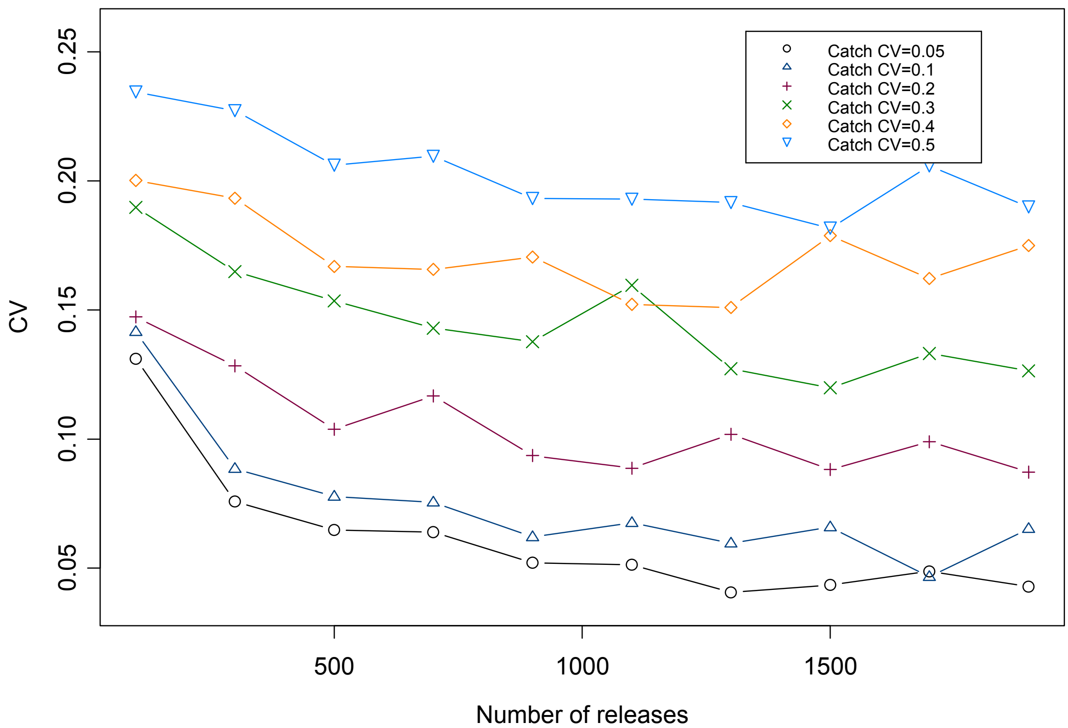
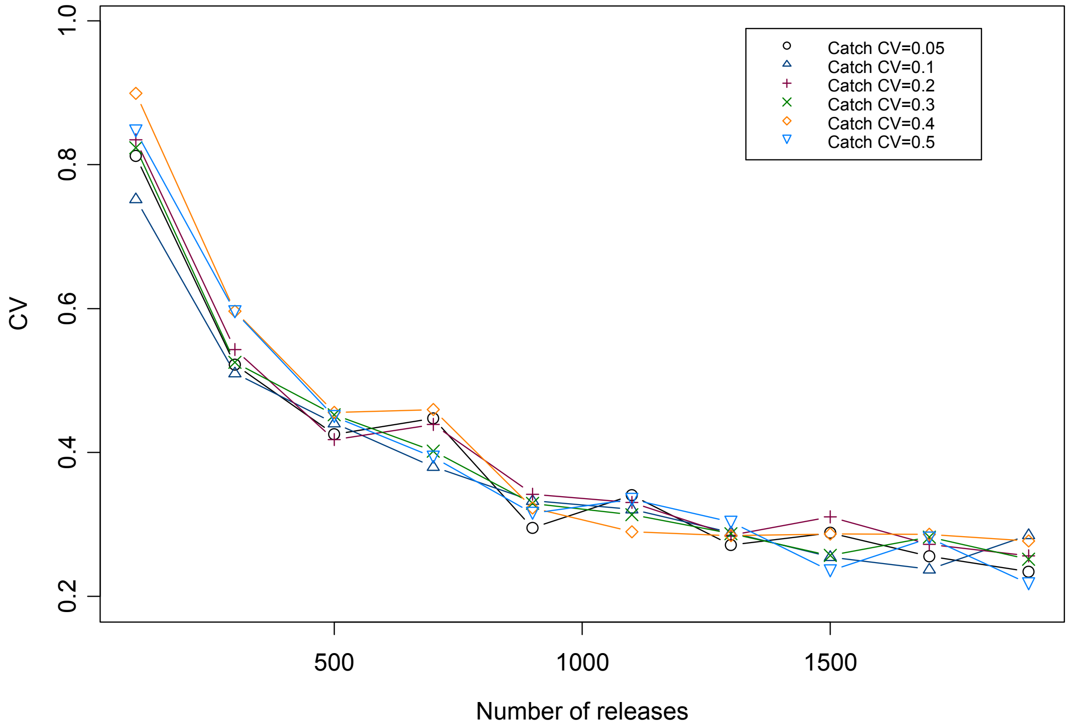


Figure 2 cont.

g) M_1



h) M_2

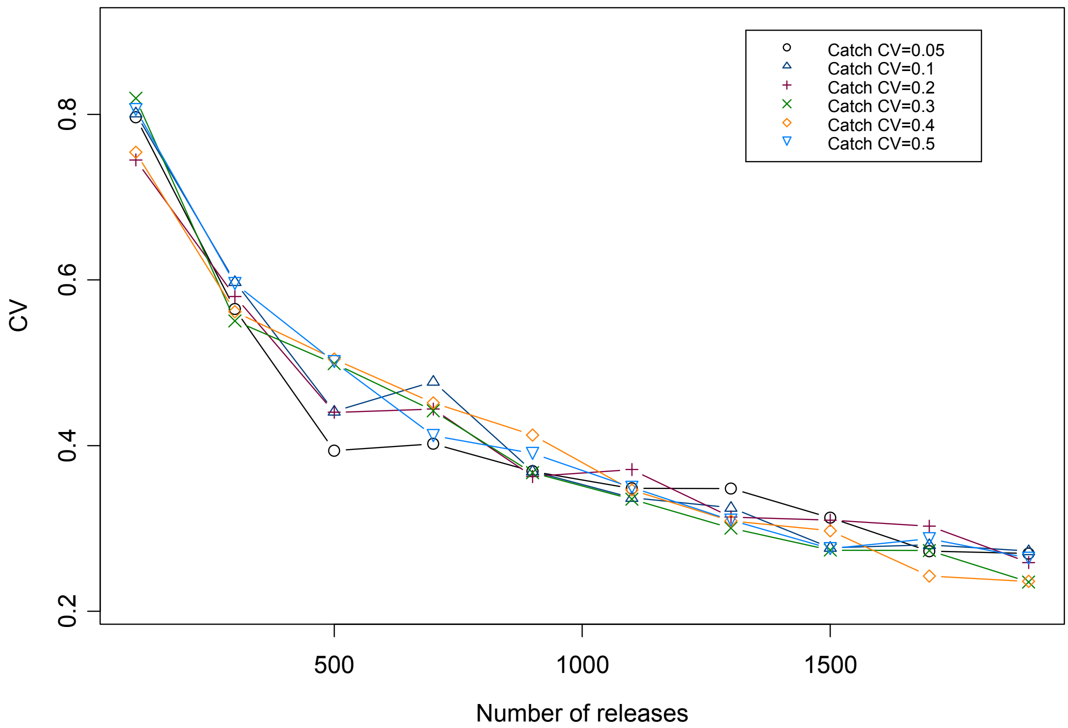


Figure 3. The assumed relationship between level of observer coverage and accuracy (i.e. the coefficient of variation) of the catch at age data.

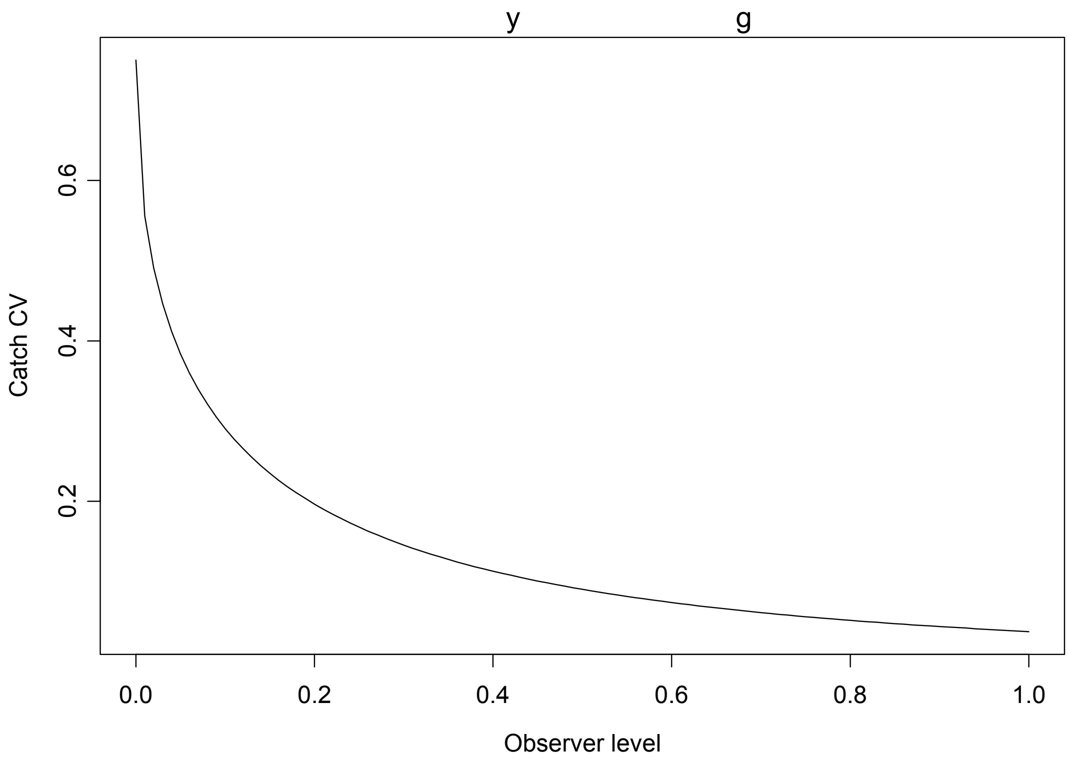
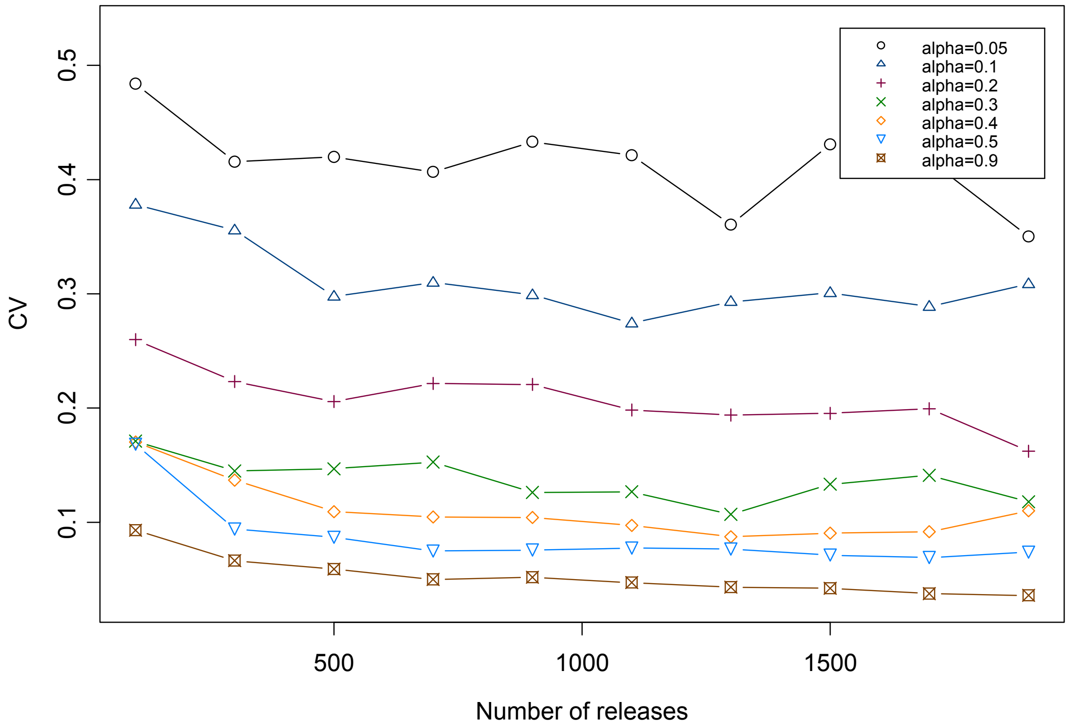


Figure 4. Effect of changing the number of releases and the level of observer coverage (alpha) on the coefficient of variation of the fishing mortality rate estimates (a-e), the population size estimate (f), and the mortality rate estimates (g-h) when reporting rates are estimated from observer data, *and the variability in the catch data is assumed to be directly related to the level of observer coverage.*

a) F_1



b) F_2

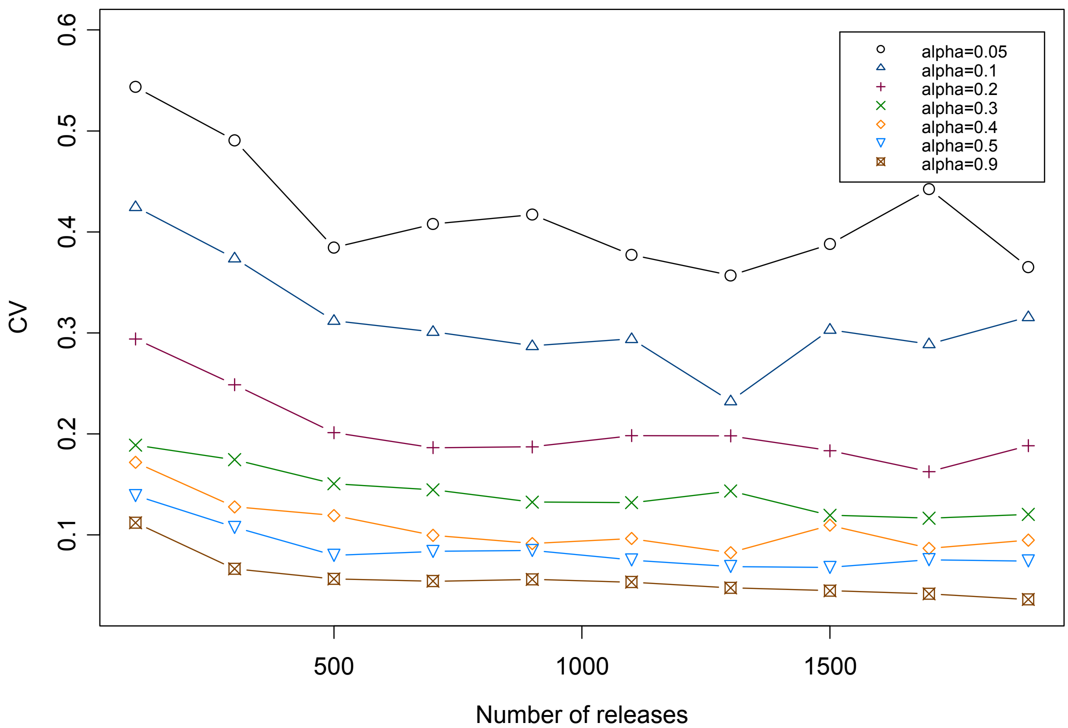
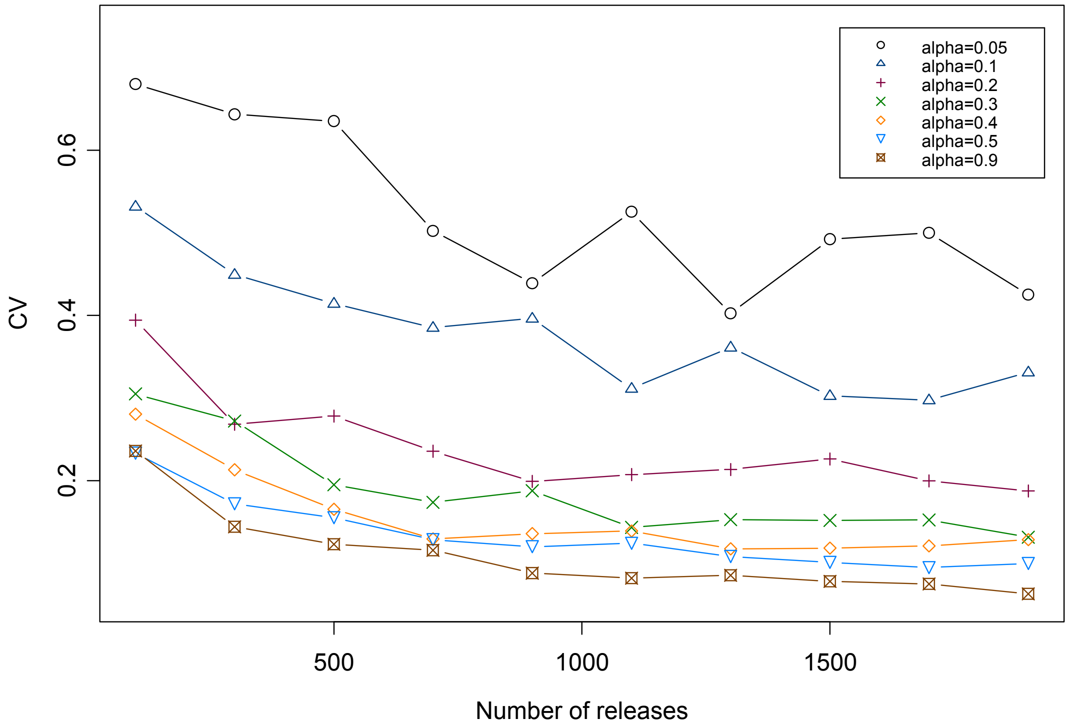


Figure 4 cont.

c) F_3



d) F_4

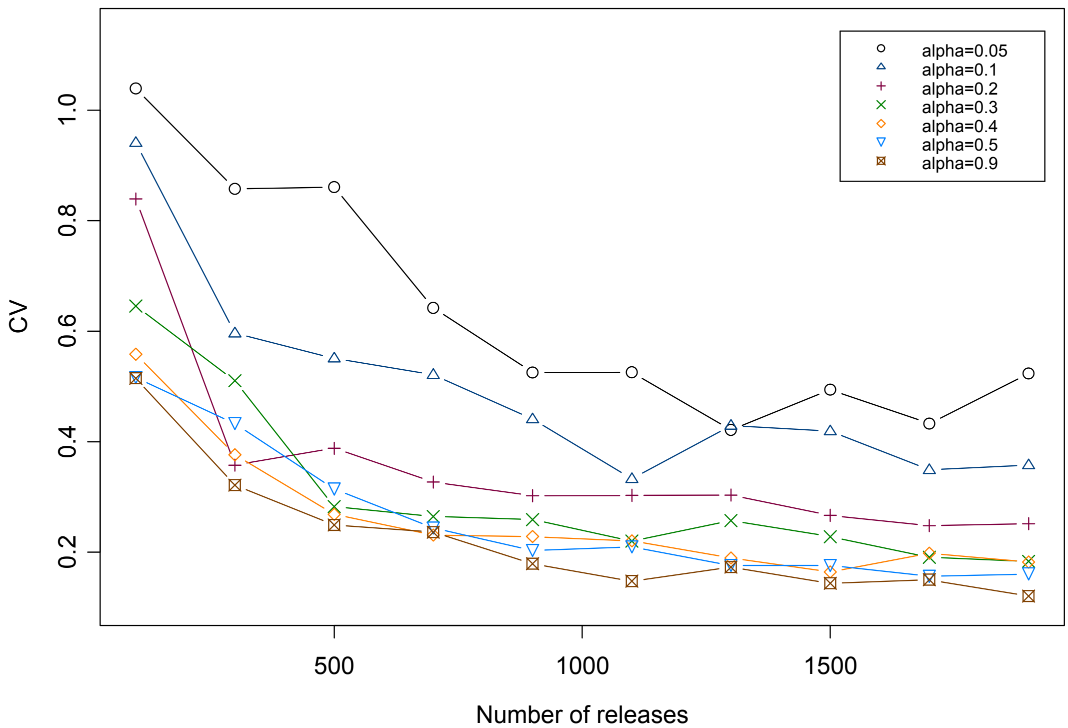
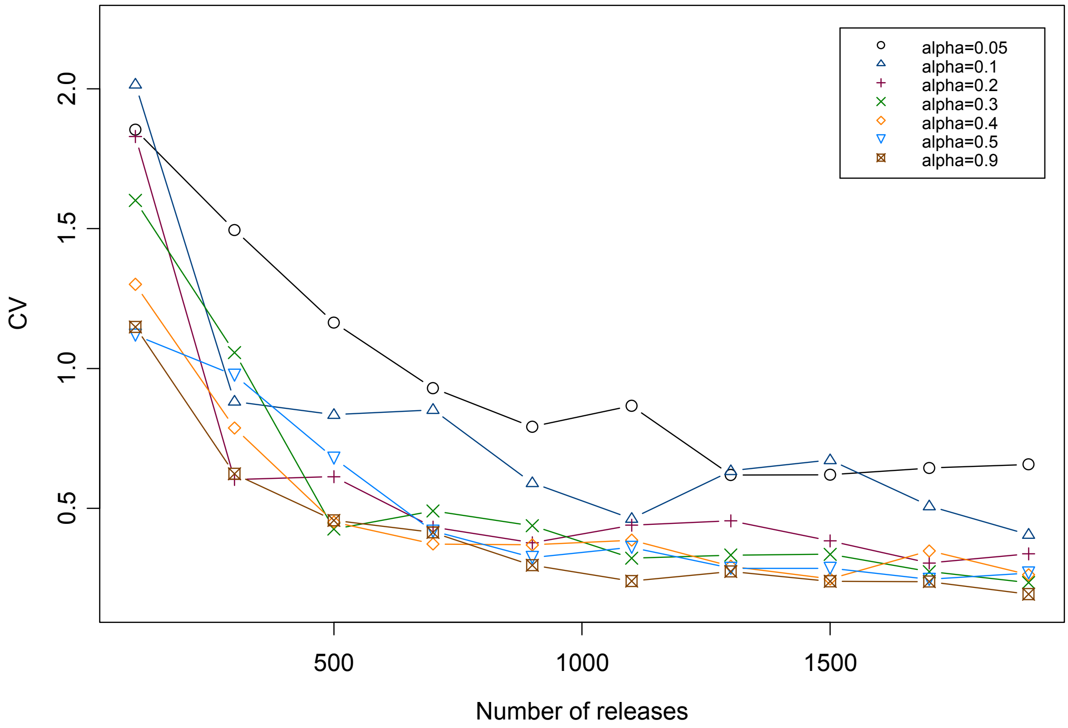


Figure 4 cont.

e) F_5



f) P_1

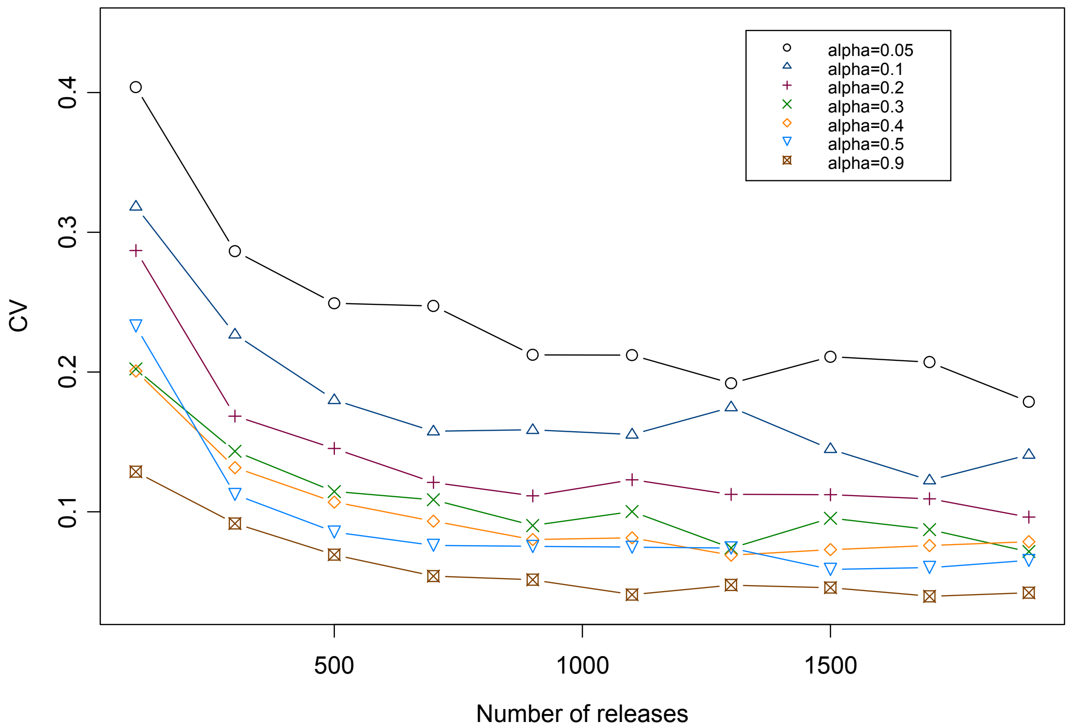
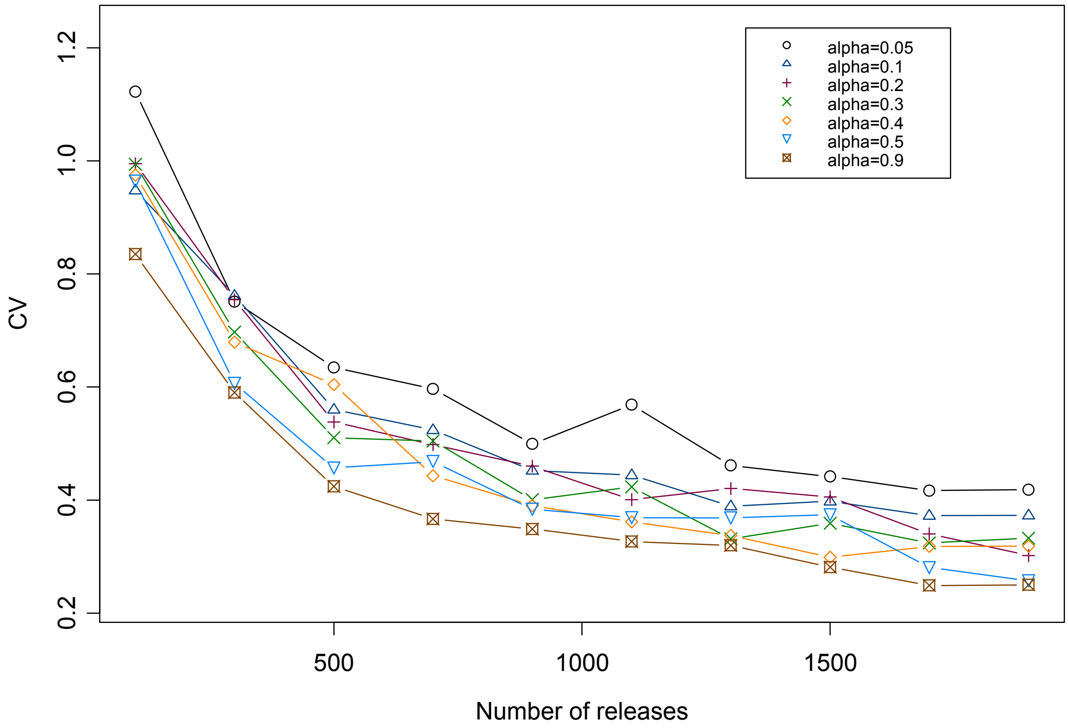


Figure 4 cont.

g) M_1



h) M_2

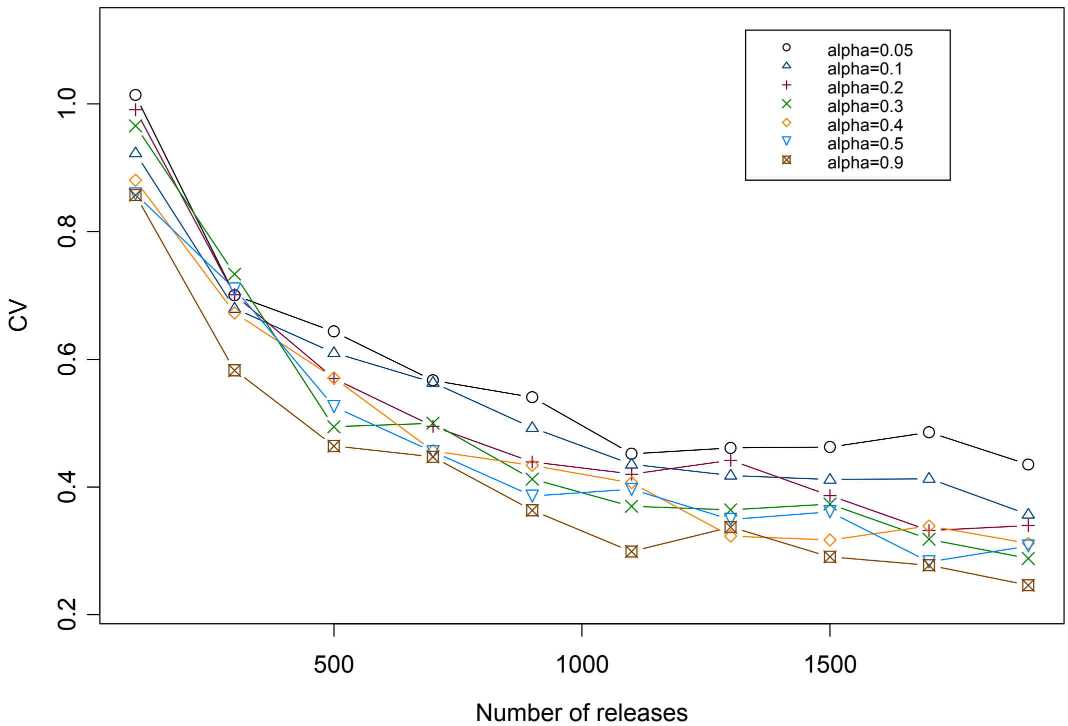
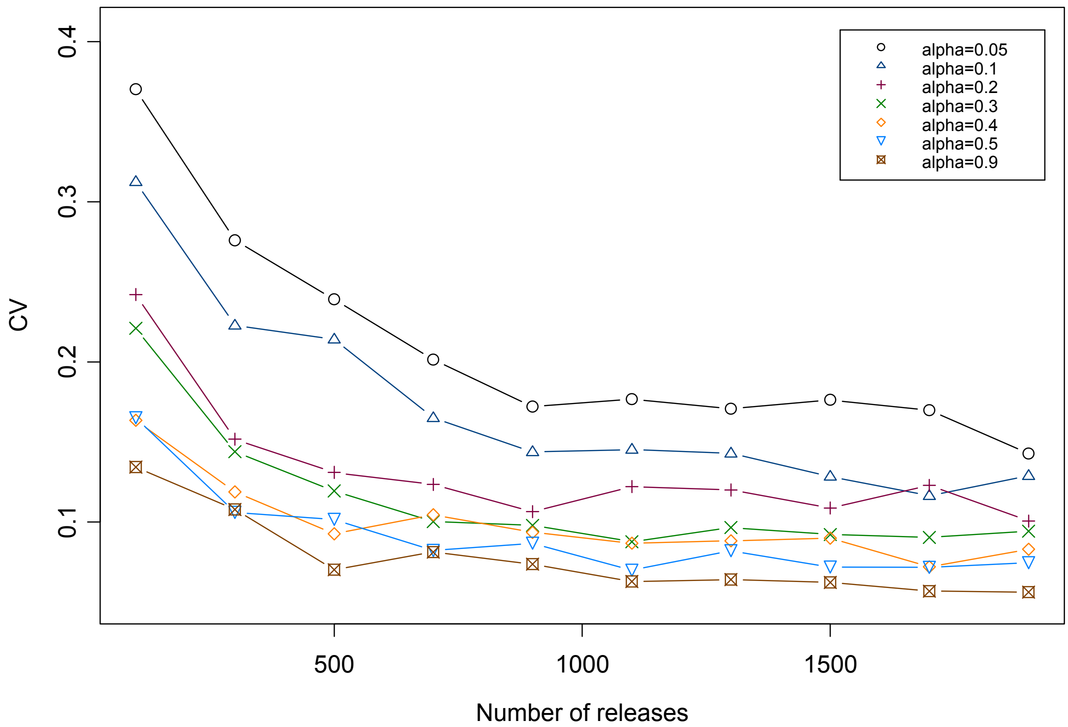


Figure 5. Effect of changing the number of releases and the level of observer coverage (alpha) on the coefficient of variation of the fishing mortality rate estimates (a-e), the population size estimate (f), and the mortality rate estimates (g-h) when reporting rates are estimated from observer data, *and the variability in the catch data is assumed to be* 0.1 *regardless of the level of observer coverage*.

a) F_1



b) F_2

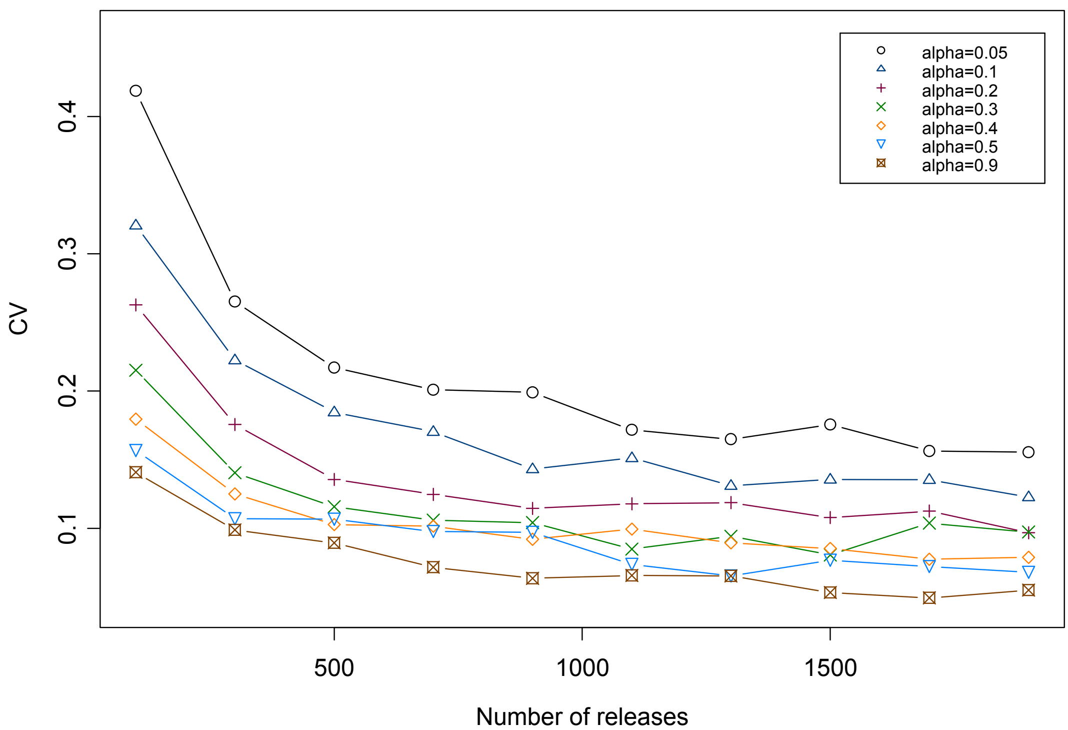
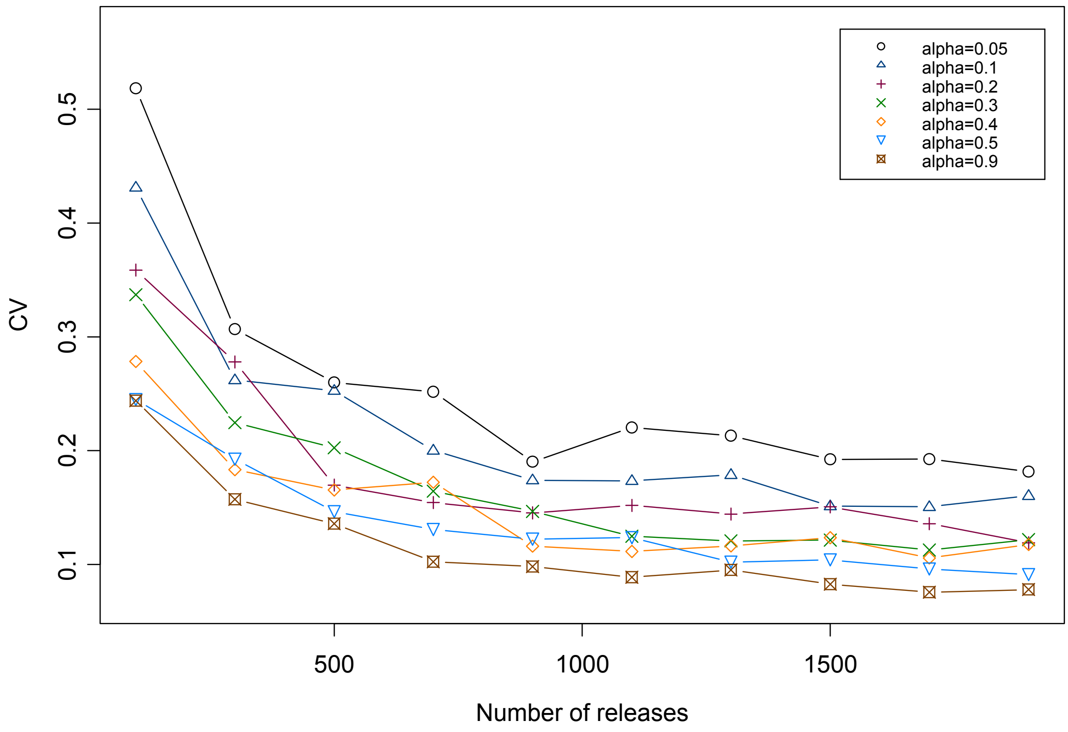


Figure 5 cont.

c) F_3



d) F_4

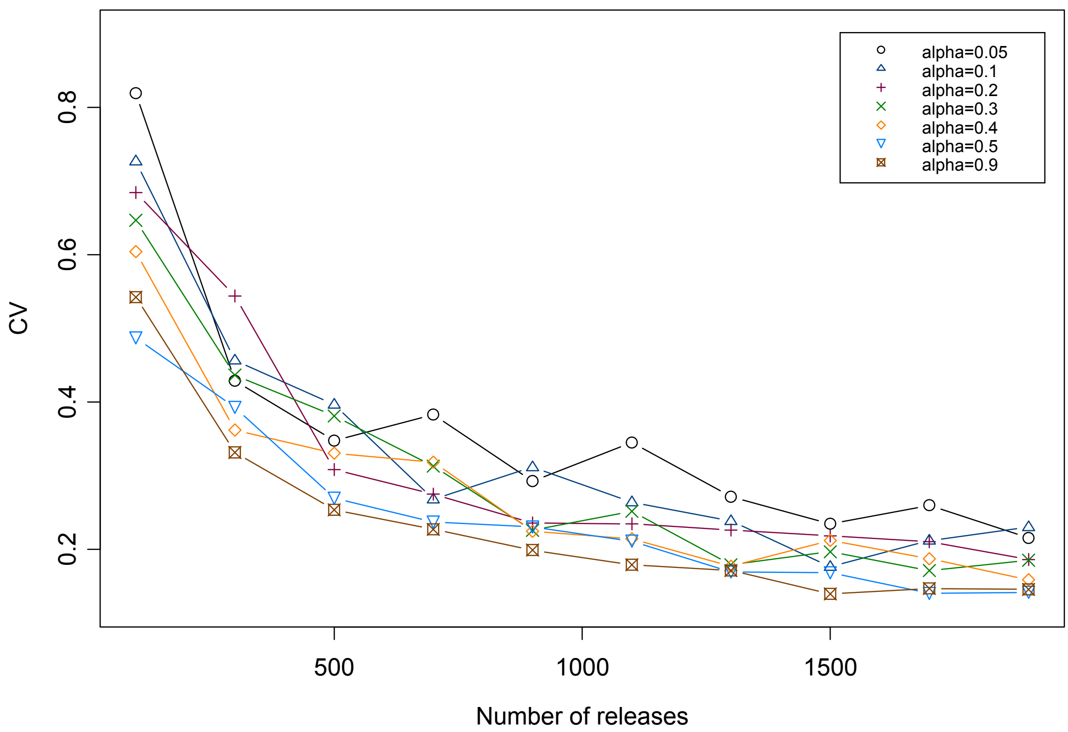
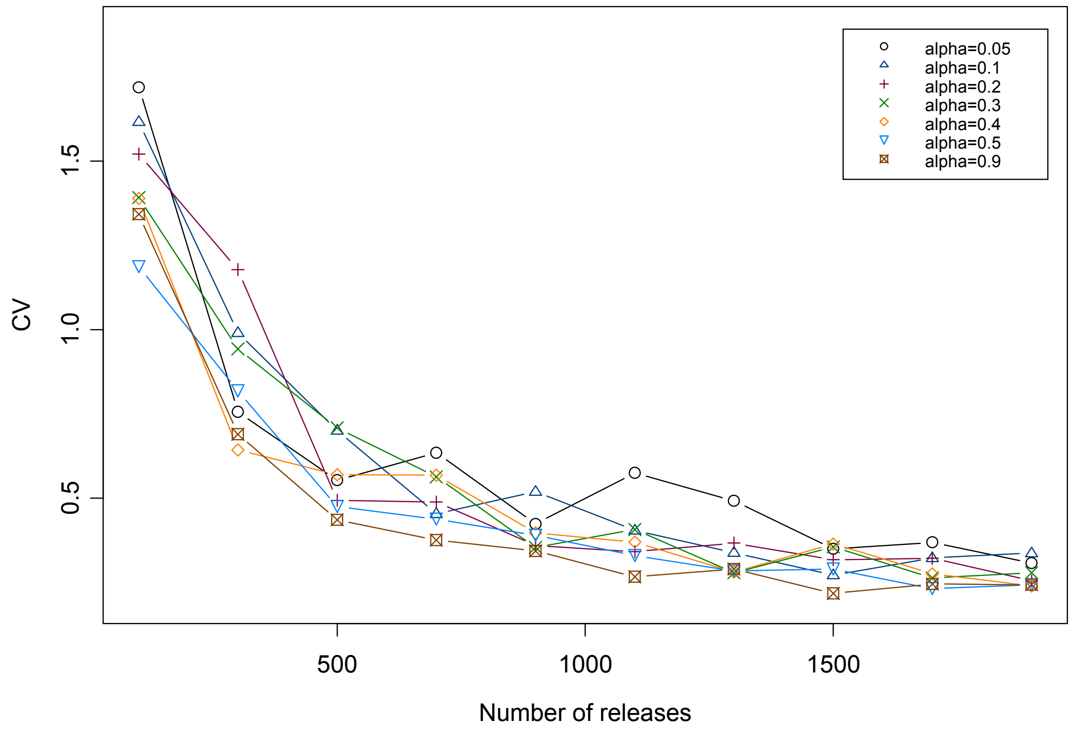


Figure 5 cont.

e) F_5



f) P_1

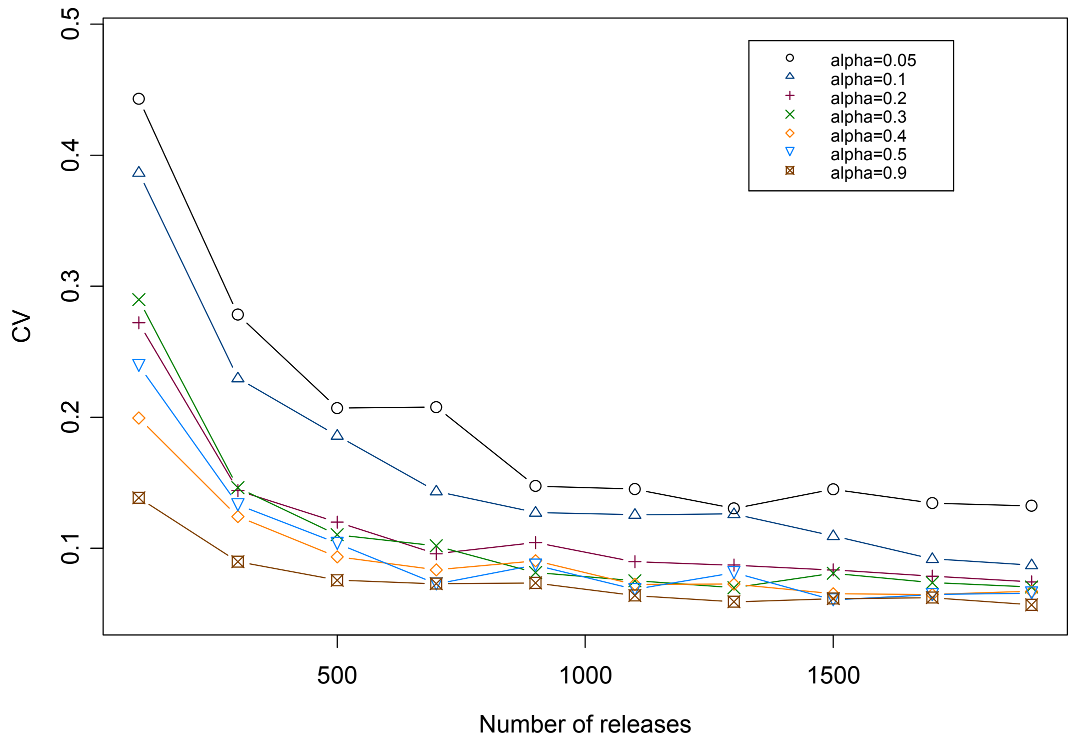
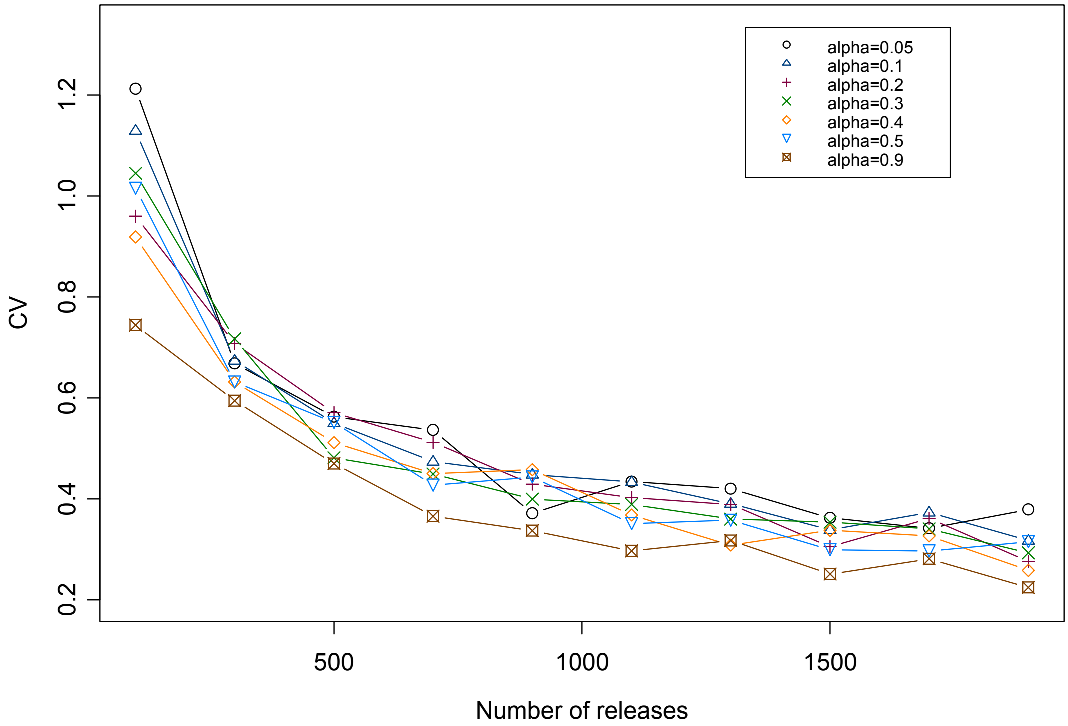


Figure 5 cont.

g) M_1



h) M_2