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# APPLICATION OF THE BROWNIE-PETERSEN METHOD FOR ESTIMATING MORTALITY RATES AND ABUNDANCE TO INDIAN OCEAN YELLOWFIN TUNA TAG-RECAPTURE AND CATCH DATA

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## Abstract

The Brownie-Petersen method for estimating mortality rates and abundance was applied to yellowfin tuna (*Thunnus albacores*) tag-recapture data and catch data from the Indian Ocean in years 2005 to 2007. The results presented are for a model with a half-yearly time-step and a single fishery (i.e., tag returns and catches were aggregated across fisheries within each time period). Several alternative scenarios were considered and the results could vary significantly between them, particularly when different growth curves were used to age the data. However, overall, the results suggest: natural mortality between ages 0 and 1 years is high but then declines rapidly; fishing mortality rates vary significantly between years and ages, but were highest for age classes 1, 1.5 and 2 years; and abundance has declined over time. When interpreting the results, it is important to note that a large number of uncertainties exist in the data and the model assumptions, as discussed in the paper. The results presented can only be considered preliminary until some of these issues have been resolved and further sensitivity runs have been conducted.


## Introduction

The Brownie-Petersen (BP) method, presented in Polacheck et al. (2006), is a method for estimating natural mortality rates, fishing mortality rates and abundance from multi-year tagging data integrated with catch data. The inclusion of catch data not only improves estimation of mortality rates (especially fishing mortality) but also allows for direct estimation of cohort size at the time of tagging. This method provides a potentially powerful alternative to CPUE and fishery-independent surveys for augmenting traditional stock assessments.

In this paper, we apply the BP method to Indian Ocean yellowfin tuna (YFT) tag-recapture and catch data. As part of a large-scale conventional tagging program, referred to as the Regional Tuna Tagging Project - Indian Ocean (RTTP-IO), large numbers of YFT (as well as skipjack (SKJ) and bigeye (BET)) were tagged between October 2005 and August 2007. Tagging occurred in the western Indian Ocean, primarily off Tanzania. Details of the RTTP-IO tagging operations can be found in Hallier (2008). Additional tagging has also occurred in the eastern Indian Ocean as part of small-scale tagging operations, including extensive tagging of YFT and SKJ off the Maldives in 2004 and 2007-2009. In total, over 63 000 YFT have been tagged since 2004. Recaptures have occurred in the commercial fisheries operating in the Indian Ocean, with returns coming primarily from the purse seine fishery. The low number of returns from other fisheries is partly due to lower catch numbers, particularly of the smaller size classes that were tagged, but probably due in most-part to non-reporting. To date, the percent of tag returns for YFT is approximately 16%. These data have the potential to provide valuable information for assessing the stock.

The stock assessment for Indian Ocean YFT that was conducted in 2011 using MULTIFAN-CL (Langley et al. 2011) suggests that total biomass has declined rapidly since the 1980s, and that recruitment in recent years has been low, particularly during 2003-2006. Recent (2006-2009) exploitation rates are also estimated to be at historically high levels. Nevertheless, for most model runs except those assuming the lowest productivity (steepness), the current exploitation rates were still estimated to be below the MSY-based reference level.

The declining trend in abundance and recruitment estimates has led to concern about the status of the Indian Ocean YFT stock. As such, it is valuable to have independent estimates of mortality rates and abundance from the BP analysis to compare with the stock assessment estimates. Although the MULTIFAN-CL stock assessment incorporates tag-recapture data, the likelihood for the tagging does not keep track of multiple releases of the same cohort, and therefore does not fully exploit the information content in the tagging data on natural morality. Furthermore, integrated stock assessment models such as MULTIFAN-CL attempt to estimate the entire age structure and history of a population since the beginning of exploitation. The models are over-parameterized and various assumptions and penalty terms, particularly with respect to catchability and selectivity, are required to yield an identifiable set of parameters. On the other hand, the BP model allows for all parameters to be estimated without requiring any assumptions about selectivity and catchability. As a result, the model can be used to test a suite of assumptions with regard to the parameters, such as whether fishing mortality can adequately be described using a selectivity function or whether certain parameters are common between ages or years. Of course, a disadvantage is that estimates are only possible for cohorts and ages for which tagging data are available. Thus, the BP model should be viewed as being complementary to the stock assessment model.

Another potential advantage of the BP model over traditional stock assessment models is that it does not rely on the use of catch per unit effort (CPUE) data. CPUE data from the longline fisheries form the principal index of stock abundance in the MULTIFAN-CL assessment for YFT in the Indian Ocean (Langley et al. 2011), but are also one of the more uncertain and unreliable components. Tagging data provide a useful alternative to CPUE data, and are perhaps the only viable alternative in fisheries, such as that for Indian Ocean YFT, where fishery-independent surveys are not possible.

## Methods

The BP method is presented in detail in Polacheck et al. (2006), but the relevant information is reproduced here for convenient reference. Modifications that were used in the application to the YFT data are also described. Note that the model is presented in terms of an annual time-step; however, it is simply a matter of replacing year with ‘time period’ for a model with a different time-step (such as quarterly or half-yearly).

### *Population dynamics 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 one time step is

$$P_{i,t+1} = P_{i,t} \exp\{-F_{i,t} - M_{i,t}\} \qquad (1)$$

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

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. Here, we focus on a multi-year tagging experiment involving a single cohort. As such, we will drop the $t$ subscript and express everything in terms of age.

Note that the model and equations are presented in terms of a single cohort as this is the minimum required by the model and makes the notation simpler. In practice, it is likely that several cohorts (age-classes) would be tagged in each time period of tagging. To include multiple cohorts in the model, one simply needs to develop the likelihood for each cohort as described in the next section, and then multiply them together to form a joint likelihood. Note that if all parameters being estimated vary with both year and age, then maximizing the likelihood for each cohort separately is equivalent to maximizing the joint likelihood (i.e., will yield the same parameter estimates). More likely, however, some parameters will be shared; for example, if natural mortality varies with age but not with year, then all fish recaptured at a given age will have a common $M$ parameter regardless of the year.

In the context of a tagging experiment, the above equations provide the basis for predicting the expected number of returns assuming that the tagged 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 $a$ ($R_{a,i}$) are given by the expressions in Table 1.

**Table 1.** Expressions for the expected number of tag returns by age corresponding to releases at a particular age, for a tagging experiment in which a cohort of fish is tagged at ages 1 to 3 and recaptured at ages 1 to 5.

| 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
$f_i = F_i/(M_i+F_i)*[1 - \exp\{-(M_i+F_i)\}]$

$S_i = \exp\{-(M_i+F_i)\}$
$\lambda_i$= 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. In our application to the YFT data, we modify the equations to incorporate tag shedding as follows:

$$f_i = \alpha F_i/(M_i+F_i+\Omega)*[1 - \exp\{-(M_i+F_i+\Omega)\}]$$
$$S_i = \exp\{-(M_i+F_i+\Omega)\}$$

where $\alpha$ is the instantaneous retention rate (i.e., the proportion of tags that are not shed immediately after tagging) and $\Omega$ is the continuous shedding rate (i.e., the rate at which tags shed over time).

Note that these modified equations pertain to single-tagged fish, but for simplicity we assume here that they hold for double-tagged fish as well. In actuality, the probability of a fish retaining (at least) one tag will be greater for a double-tagged fish than a single-tagged fish; however, for YFT, the shedding rate estimates are low enough (see ‘Data and assumptions’ section below) that we assume the difference can be ignored.

We also want to account for the fact that newly tagged fish will not be fully mixed with the untagged population immediately after tagging, and for the fact that tagging generally occurs during the fishing season so tagged fish are only vulnerable for part of the season. To do so, we allow the *F* parameters to differ between tagged and untagged fish in one or more time periods after tagging (see application to southern bluefin tuna in Polacheck et al. 2006).

Equations (1) and (2) can also be used to provide analogous expressions for the expected catches of age *i* fish from a particular cohort, conditional on the size of the cohort at the age of first tagging, assumed here to be age 1 and denoted by $P_1$ (Table 2).

**Table 2.** Expressions for the expected number of fish caught at ages 1 to 5 from a cohort which had an age 1 abundance of $P_1$.

| Size of cohort | Expected catch from age class *i* | | | | |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 |
| $P_1$ | $P_1f_1$ | $P_1S_1f_2$ | $P_1S_1S_2f_3$ | $P_1S_1S_2S_3f_4$ | $P_1S_1S_2S_3S_4f_5$ |

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 there is little uncertainty in the numbers of tags returned[1], the numbers of fish caught at each age will be estimated quantities. These

[1] The numbers of tags *recaptured* can have high uncertainty due to uncertain reporting rates, but the numbers of tags actually returned (i.e., the data that enters the model) are usually known accurately.

quantities are usually derived from a multi-stage sampling of catches for length combined with age-length keys derived from otoliths, or obtained via cohort slicing. Because $P_1$ is unknown, it is not possible to derive estimates of mortality rates from the catch at age data alone[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*

As developed in Brownie et al. (1985), if each tag recapture is assumed to be independent, then the numbers of returns at age corresponding to a given release event are expected to be multinomial. The likelihood function for the observed numbers of returns from all release events is the product of multinomials:

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

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 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.

Variance in the tag return numbers may be greater than a multinomial distribution predicts (due to factors such as tagged fish remaining in schools). Overdispersion (i.e., extra variability) can be accounted for by using a Dirichlet-multinomial distribution, but this requires specifying the level of overdispersion since it cannot be reliably estimated within the model. Assuming a multinomial distribution, as we have done in the analyses presented here, should not bias the parameter estimates; however, it means that their estimated standard errors will be too small if that return data are in fact overdispersed (Polacheck et al. 2006).

Similar to the tag-return data, if we assume that all fish in a cohort are independent, then the catch at age data can be modelled as random multinomial, where each fish has a probability of being captured at age $i$. Expressions for the catch probabilities can be obtained by dividing the expected catches in Table 2 by the initial cohort size, $P_1$.

[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.

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), $\upsilon$, 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 (see Polacheck et al. 2006). 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 $\upsilon$ cannot be estimated from the data when a separate *F* is estimated for each year of recapture, thus we assume that it is known.

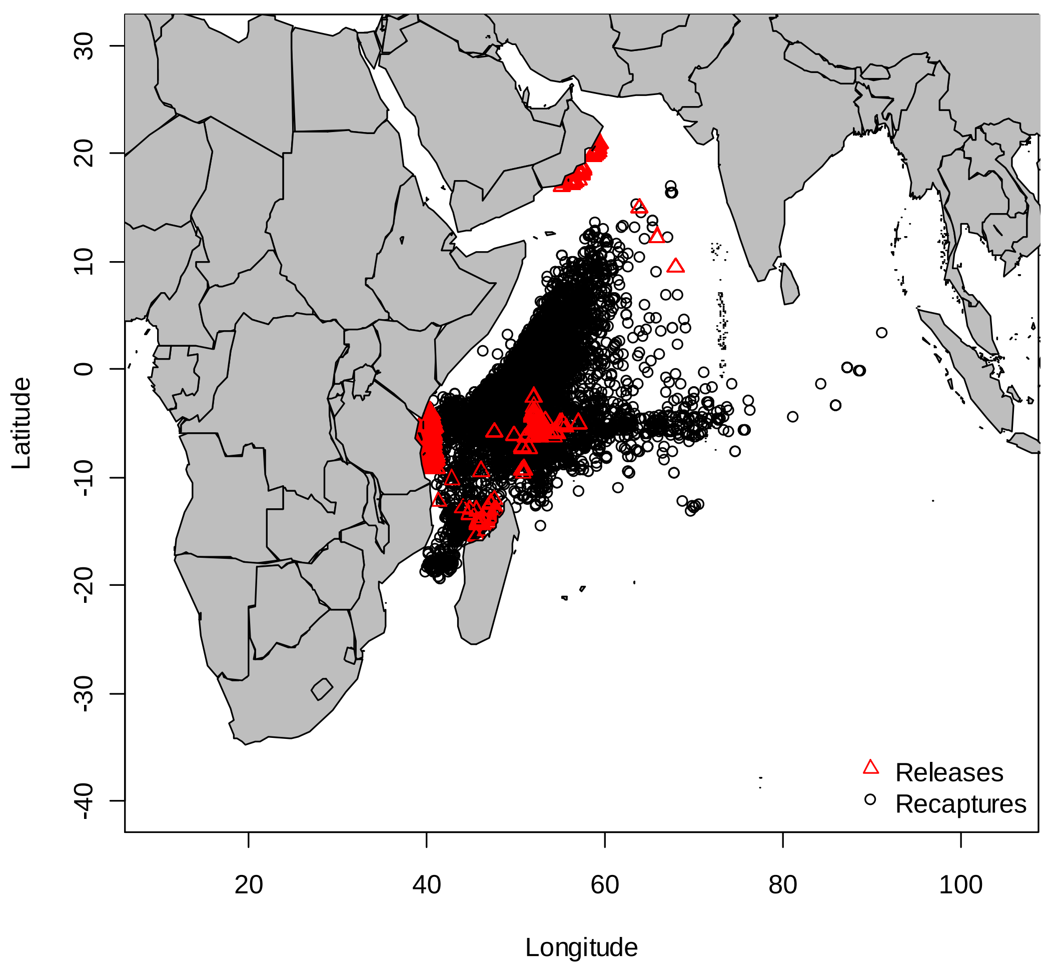
The information for estimating $M_i$ comes from the differential between the expected returns at age $i+1$ of fish released at age *i* and those released at age $i+1$. Thus, in an experiment with *n* release events, estimates can only be obtained for $M_i$ to $M_{n-1}$ because subsequent *M*'s are not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

## Data and assumptions

After considering annual, half-yearly and quarterly time-steps, a half-yearly time-step was decided upon. This seemed to provide a fine enough scale not to blur the differences in mortality rates at the young age classes, but broad enough that the tag and recapture sample sizes were sufficient for most time periods and age classes.

Only YFT tag-recapture data from the RTTP-IO were used here (database version 2012-09-21); data from the small-scale tagging projects were not included because there is greater uncertainty in their reliability. Furthermore, only returns from the purse seine (PS) fishery were included since return rates from the other fisheries are very low and reporting rate estimates are either not available or much less certain than those for the PS fishery. A screening criteria was applied to the RTTP-IO releases to ensure only reliable data were included. Specifically, releases were only included where: species identification was considered reliable (i.e., TAG_SpRel=1 in the IOTC tag database), the fish was in good condition after tagging (TAG_FishRel=1), the tag (or at least one tag in the case of double tagging) was inserted well (TAG_Tag1Rel=1 or TAG_Tag2Rel=1), fish length (needed to estimate age) was measured reliably (TAG_LengthRel=1). All recaptures corresponding to these releases were included, even though the date of recapture (used to estimate recapture age) may not be considered reliable; we cannot exclude recaptures without accounting for them in some way or we would bias the results. Figure 1 shows the locations of YFT releases and recaptures that were available for analysis after the above criteria were applied.

**Figure 1.** Release and recapture locations of YFT considered suitable for the Brownie-Petersen analysis. Only RTTP-IO releases and purse seine recaptures are included.




One of the key assumptions of the BP model is that tagged fish are fully mixed with the population of untagged fish within a specified time period after release. Langley and Million (2012) investigated this issue to determine an appropriate mixing period for use in the YFT stock assessment and recommended that a mixing period of 3 quarters (9 months) be used; sensitivity of the stock assessment results to the mixing period was also investigated (Langley 2012). Using this recommendation as a guide for the half-yearly BP model, we used a mixing period of 6 months (1 time period) as the default, but also conducted a sensitivity run using a mixing period of 12 months (2 time periods).

A comparison of return rates from RTTP-IO releases from different areas shows that a large percent (~10%) of the Kenya and Madagascar releases were returned in the first 90 days (Table 3). However, if we exclude returns in the first 90 days, then ~14% of the Kenya, Seychelles and Tanzania releases, and ~10% of the Madagascar and international releases, are returned in the PS fishery (Table 3). In comparison, only 1.1% of the 2748 Oman releases were returned in the PS fishery. Even if half the fish tagged off Oman were caught in other fisheries but not reported, this would still mean only 2% returns from the PS fishery. The reason for such a low return rate from the Oman releases is unclear and needs further investigation. For now, we fit the BP models both with and without the Oman releases to assess the sensitivity of the results to these releases.

**Table 3.** Number of releases by country of release and (i) percent returns within 90 days at liberty and (ii) total percent returns.
INT=international, KEN=Kenya, MAD=Madagascar,OMA=Oman, SEY=Seychelles, TAN=Tanzania. (Only countries with>100 releases are included.)

| Release country | Number releases | Percent returns ≤90 days | >90 days |
|---|---|---|---|
| INT | 316 | 1.9 | 10.8 |
| KEN | 803 | 9.5 | 14.0 |
| MAD | 393 | 11.7 | 11.0 |
| OMA | 2748 | 0.0 | 1.1 |
| SEY | 3093 | 1.5 | 14.2 |
| TAN | 43770 | 3.4 | 14.7 |

The YFT catch data used here were compiled by the IOTC Secretariat for the MULTIFAN-CL stock assessment, and are broken down by year, quarter, fishery and assessment area[3]. In each year-quarter-fishery combination that had length information, the sample length-frequency data was scaled up to the total catch in that year, quarter and fishery. For a year-quarter-fishery combination that did not have any length information, the length-frequency data for that fishery from adjacent years (usually ±1 year was adequate, but up to ±5 years was necessary in some cases) were combined to calculate a length-frequency distribution[4], which was then scaled up to

[3] The analyses presented here did not make use of the spatial information, but in future it would be worth exploring spatial applications of the Brownie-Petersen model to the YFT data (see Discussion).
[4] The troll fishery has almost no length information, so length-frequency information from the longline fishery was used (i.e., for a given year-area-quarter, the length-frequency distribution for the troll fishery was assumed to be the same as for the longline fishery).

the total catch for that year, quarter and fishery. Catch data are not essential to the model; without these data the model becomes a Brownie model and abundance can no longer be estimated (only natural mortality and fishing mortality). Catch data, and especially length information, for much of the Indian Ocean YFT catches are not reliable; thus we ran the models with and without catch data to see the sensitivity of the results and to check for consistency between the catch and tag-recapture datasets.

The release data and the catch data were aged based on length using an assumed growth curve and a simple 'cohort slicing' method (i.e., fish with lengths between L($a_1$) and L($a_2$) are considered to be age $a_1$, where L($a$) is the expected length at age $a$ calculated from the growth curve). The growth curve we used was taken from Eveson et al. (2012), in which a VB log k model (von Bertalanffy with a logistic growth rate parameter) was fit to the most recent tag-recapture and otolith data for YFT. Several variations of the VB log k model were presented (see Figure Y7 of Eveson et al. 2012); however, we have chosen to use the model in which the otolith data were highly weighted (wt=100) and the mean asymptotic length parameter was fixed at 145cm as our default (Figure 2, dashed blue line). As a sensitivity run, we also used the VB log k growth curve with the mean asymptotic length parameter fixed at 145cm, but the otolith data not weighted (wt=1) (Figure 2, solid green line).

Figure 2. The VB log k growth curves used for ageing the YFT release length data and catch-at-length data.

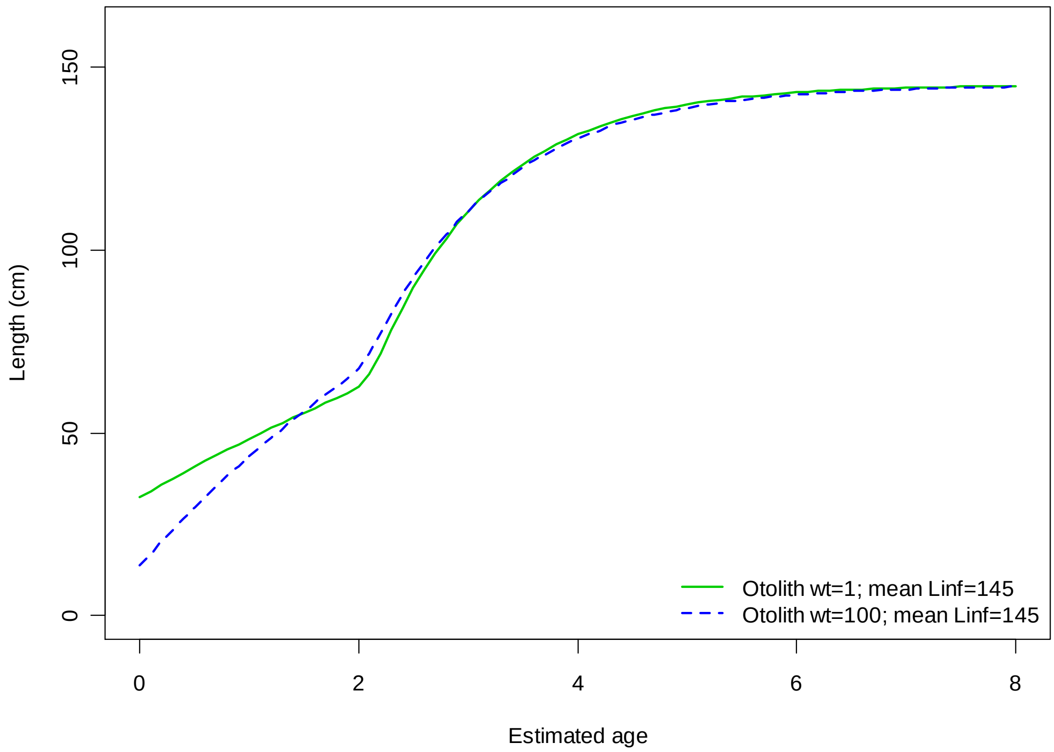



Table 4 gives a summary of the data that were input to the BP model with a half-yearly time-step, in the format required for the model. In particular, the release and recapture data (Table 4a) are broken down by cohort and age of release, and age at recapture. Our convention is to refer to the lower bound of each time period and age class, so time period 2004.0 refers to 2004 months 1-6 and 2004.5 refers to 2004 months 7-12, and age class 0.5 refers to 0.5-1 yrs old and 1.0 refers to 1-1.5 yrs old. The BP method requires a cohort to be tagged in multiple consecutive time periods in order to separate *M* from *F*, so only cohorts 2003.5 to 2006.5 had sufficient data to be included in the analysis. Almost all fish (>99%) were tagged at ages 0.5 to 2.5, so only these release ages were included in the model. Also, the numbers of recaptures beyond age 5.5 are too small to be informative, so only recaptures at ages 0.5 to 5.5 are included. Note that each cohort was not tagged at all release ages (e.g., cohort 2003.5 was not tagged at ages 0.5 or 1.0 since this was before the RTTP-IO began), but this is not a problem for the model to deal with. The catch data (Table 4b) are broken down by cohort and age. Release age and age of the catch were estimated using the default VB log k growth curve described above (i.e., the blue dashed line in Figure 2). Recapture age was calculated from the estimated release age plus the time at liberty. Cohort was calculated as time period (of tagging or catch) minus estimated age.

**Table 4.** YFT data used in the Brownie-Petersen model with a half-yearly time-step. (a) Number of tag releases by cohort and release age, and corresponding number of tag returns by age. Only RTTP-IO releases and returns from the purse seine fishery are included. (b) Catch numbers (in millions) by cohort and age. Age was estimated from length using the default VB log k growth curve (dashed blue line in Figure 2). Cohort 200x.0 refers to fish born in year 200x months 1-6, cohort 200x.5 refers to fish born in year 200x months 7-12. Age gives the lower bound of the half-yearly age class (e.g., age 0.5 refers to fish of ages 0.5 to 1 years).

(a) Release-recapture data

| | Release | Release | Number | Number returns by age | | | | | | | | | | | | Total | Percent |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cohort | age | year | releases | 0.5 | 1.0 | 1.5 | 2.0 | 2.5 | 3.0 | 3.5 | 4.0 | 4.5 | 5.0 | 5.5 | 6.0+ | returns | returns |
| 2003.5 | 1.5 | 2005 | 370 | 0 | 0 | 37 | 1 | 6 | 11 | 6 | 3 | 3 | 0 | 1 | 2 | 70 | 18.9 |
| 2003.5 | 2.0 | 2005 | 543 | 0 | 0 | 0 | 0 | 8 | 20 | 11 | 9 | 4 | 2 | 0 | 1 | 55 | 10.1 |
| 2003.5 | 2.5 | 2006 | 784 | 0 | 0 | 0 | 0 | 20 | 28 | 28 | 9 | 14 | 2 | 1 | 1 | 103 | 13.1 |
| 2004.0 | 1.0 | 2005 | 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.0 |
| 2004.0 | 1.5 | 2005 | 2806 | 0 | 0 | 10 | 60 | 66 | 39 | 45 | 14 | 4 | 2 | 3 | 3 | 246 | 8.8 |
| 2004.0 | 2.0 | 2006 | 1056 | 0 | 0 | 0 | 20 | 49 | 28 | 14 | 22 | 4 | 1 | 1 | 0 | 139 | 13.2 |
| 2004.5 | 0.5 | 2005 | 6 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 16.7 |
| 2004.5 | 1.0 | 2005 | 1083 | 0 | 5 | 42 | 19 | 28 | 23 | 17 | 6 | 2 | 0 | 1 | 1 | 144 | 13.3 |
| 2004.5 | 1.5 | 2006 | 10546 | 0 | 0 | 110 | 624 | 445 | 304 | 220 | 103 | 60 | 25 | 19 | 12 | 1922 | 18.2 |
| 2004.5 | 2.0 | 2006 | 1499 | 0 | 0 | 0 | 64 | 141 | 68 | 40 | 14 | 7 | 2 | 3 | 4 | 343 | 22.9 |
| 2004.5 | 2.5 | 2007 | 826 | 0 | 0 | 0 | 0 | 2 | 6 | 3 | 1 | 2 | 0 | 0 | 1 | 15 | 1.8 |
| 2005.0 | 0.5 | 2005 | 4 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 25.0 |
| 2005.0 | 1.0 | 2006 | 2199 | 0 | 37 | 233 | 54 | 21 | 12 | 10 | 5 | 2 | 4 | 0 | 1 | 379 | 17.2 |
| 2005.0 | 1.5 | 2006 | 7551 | 0 | 0 | 310 | 403 | 232 | 170 | 88 | 32 | 26 | 12 | 2 | 9 | 1284 | 17.0 |
| 2005.0 | 2.0 | 2007 | 1403 | 0 | 0 | 0 | 4 | 29 | 2 | 1 | 1 | 0 | 0 | 0 | 0 | 37 | 2.6 |
| 2005.0 | 2.5 | 2007 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.0 |
| 2005.5 | 0.5 | 2006 | 975 | 8 | 64 | 10 | 0 | 4 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 87 | 8.9 |
| 2005.5 | 1.0 | 2006 | 9544 | 0 | 395 | 820 | 382 | 175 | 114 | 60 | 63 | 23 | 12 | 16 | 17 | 2077 | 21.8 |
| 2005.5 | 1.5 | 2007 | 1196 | 0 | 0 | 0 | 159 | 36 | 18 | 7 | 14 | 4 | 3 | 0 | 4 | 245 | 20.5 |

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2005.5 | 2.0 | 2007 | 379 | 0 | 0 | 0 | 33 | 19 | 20 | 7 | 3 | 3 | 0 | 1 | 0 | 86 | 22.7 |
| 2006.0 | 0.5 | 2006 | 37 | 2 | 8 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 12 | 32.4 |
| 2006.0 | 1.0 | 2007 | 223 | 0 | 2 | 28 | 6 | 1 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 40 | 17.9 |
| 2006.0 | 1.5 | 2007 | 4819 | 0 | 0 | 290 | 165 | 116 | 58 | 59 | 32 | 10 | 6 | 6 | 11 | 753 | 15.6 |
| 2006.5 | 0.5 | 2007 | 327 | 0 | 35 | 8 | 2 | 2 | 3 | 1 | 1 | 0 | 0 | 0 | 0 | 52 | 15.9 |
| 2006.5 | 1.0 | 2007 | 1792 | 0 | 154 | 123 | 11 | 12 | 13 | 11 | 2 | 2 | 0 | 0 | 0 | 328 | 18.3 |

(b) Catch data (in millions)

| | Number caught by age | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Cohort | 0.5 | 1.0 | 1.5 | 2.0 | 2.5 | 3.0 | 3.5 | 4.0 | 4.5 | 5.0 | 5.5 |
| 2003.5 | 0.91 | 7.32 | 2.74 | 1.24 | 1.11 | 1.11 | 0.89 | 0.29 | 0.32 | 0.11 | 0.08 |
| 2004.0 | 1.69 | 2.89 | 3.94 | 2.38 | 0.96 | 1.14 | 0.58 | 0.55 | 0.19 | 0.11 | 0.09 |
| 2004.5 | 0.50 | 5.98 | 1.75 | 1.59 | 1.09 | 0.85 | 0.85 | 0.33 | 0.21 | 0.13 | 0.12 |
| 2005.0 | 1.60 | 2.14 | 6.74 | 0.93 | 0.73 | 0.97 | 0.52 | 0.37 | 0.22 | 0.17 | 0.10 |
| 2005.5 | 0.29 | 8.20 | 1.33 | 0.92 | 0.76 | 0.60 | 0.61 | 0.43 | 0.28 | 0.14 | 0.13 |
| 2006.0 | 1.53 | 3.05 | 2.25 | 0.82 | 0.36 | 0.80 | 0.63 | 0.51 | 0.26 | 0.16 | 0.10 |
| 2006.5 | 1.13 | 5.49 | 1.94 | 0.91 | 0.91 | 0.73 | 0.73 | 0.45 | 0.25 | 0.15 | |

Reporting rates are required for each time period and age of tag returns being included in the model. Although reporting of a tag is not expected to depend on the age of a fish, it is still necessary to estimate age-specific reporting rates in situations where there are multiple fisheries with different selectivities, implying different age-structures in the catches (Hearn et al. 1999). An average reporting rate across all fisheries is calculated for time period *t* and age *a* by taking a weighted average of the fishery-specific reporting rates, where the weights are the proportion of the catches in time period *t* belonging to age class *a* in each fishery. Reporting rates have been estimated from tag seeding data for the PS catches unloaded in the Seychelles (this includes both log-set and free-school catches). Estimates by year and quarter for 2004 to 2009 were provided by the IOTC Secretariat; they were not yet updated to include 2010 and 2011 at the time of the BP analysis so we assumed the reporting rates for these years were equal to the 2009 estimates from the same quarter. Reporting rates for the "at sea" PS catches are assumed to be 100%. For all other fisheries, the reporting rates are assumed to be 0% (recall that the relatively small numbers of tag returns from these fisheries have been excluded from analysis[5]). Table 5 shows the reporting rate estimates (averaged over all fisheries) that were calculated using half-yearly time periods. Note that the small values for some time periods and ages are due to the fact that the fisheries assigned a 0% reporting rate catch a large portion of the total catch for that time period and age.

**Table 5.** Reporting rate estimates (averaged over all fisheries) by cohort and age of recapture. See text for details.

| | Age | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Cohort | 0.5 | 1.0 | 1.5 | 2.0 | 2.5 | 3.0 | 3.5 | 4.0 | 4.5 | 5.0 | 5.5 |
| 2003.5 | 0.17 | 0.32 | 0.28 | 0.09 | 0.23 | 0.42 | 0.42 | 0.35 | 0.36 | 0.22 | 0.20 |
| 2004.0 | 0.38 | 0.33 | 0.39 | 0.14 | 0.32 | 0.31 | 0.40 | 0.39 | 0.26 | 0.25 | 0.13 |
| 2004.5 | 0.18 | 0.33 | 0.39 | 0.16 | 0.32 | 0.40 | 0.37 | 0.29 | 0.27 | 0.16 | 0.06 |
| 2005.0 | 0.25 | 0.51 | 0.60 | 0.11 | 0.21 | 0.29 | 0.33 | 0.28 | 0.18 | 0.08 | 0.09 |
| 2005.5 | 0.31 | 0.69 | 0.40 | 0.33 | 0.38 | 0.31 | 0.23 | 0.17 | 0.09 | 0.12 | |
| 2006.0 | 0.57 | 0.38 | 0.56 | 0.08 | 0.24 | 0.10 | 0.19 | 0.09 | 0.16 | | |
| 2006.5 | 0.14 | 0.49 | 0.35 | 0.28 | 0.13 | 0.19 | 0.11 | 0.22 | | | |

Tag shedding estimates were provided by the IOTC Secretariat; they were obtained by an update of the analysis in Gaertner and Hallier (2009). A constant rate shedding model, $Q(t) = \alpha \exp(-\Omega t)$, was found to give the best fit, with parameter values estimated to be $\alpha$=0.977 and $\Omega$=0.039 (per year). Note that Q(t) is the probability of a tag being retained after time *t*, $\alpha$ is the proportion of tags that are retained immediately after tagging, and $\Omega$ is the rate at which tags shed over time.

[5] The Maldives pole and line fishery does return some tags; however, in the absence of any information on reporting rates, it is simplest to omit these returns from the analysis and assume a 0% reporting rate for this fishery.

Recall that the CV of the catch data needs to be specified. A value of 0.3 was used here; although this value was chosen rather arbitrarily, previous investigations have shown the results to be fairly insensitive to the value used (Eveson et al. 2007).

In fitting all BP models presented here, we allowed *M* to vary with age but not across time periods, and *F* to vary with both age and time period (with no assumptions about selectivity patterns). Because we are assuming a single fishery, this means we estimate a total *F* for each time period and age (i.e., we do not estimate fishery-specific *F*s).

## Results

The results obtained from the "base" BP model run (using the default growth curve, including the Oman releases, including catch data and assuming a mixing period of 6 months) are presented in Table 6 and Figure 3. *M* is estimated to be very high at age 0.5 (~1.0 per half year so 2.0 per year) and then declines rapidly to essentially 0 by age 2.0. The *F* estimates for a given age can differ a lot between cohorts (i.e., time periods); for example, the age 2.0 *F* estimate was >0.45 for cohorts 2004.5 to 2006.0 (time periods 2006.5 to 2008.0), but was only 0.11 and 0.20 for cohorts 2003.5 and 2004.0 (time periods 2005.5 and 2006.0) respectively. Generally, the *F* estimates for ages 1.0 to 2.0 are higher than for other ages. The abundance estimates obtained from the model correspond to the size of the cohort at the age when it was first tagged so they are not all directly comparable. For example, the estimate for cohort 2003.5 of 51.0 million is for age 1.5 whereas the estimate for cohort 2004.5 of 60.2 million is for age 0.5. Abundance estimates for ages beyond the age of tagging can be derived using the estimates of F and M, and make direct comparison between cohorts easier (see Figure 3c); in particular, it can be seen that the 2003.5 and 2004.0 cohorts are estimated to have been largest.

Results from 4 alternative model runs are also plotted: (1) using the alternative growth curve (Figure 4); (2) excluding the Oman releases (Figure 5); (3) excluding catch data (Figure 6); and (4) using a mixing period of 12 months (Figure 7). The results are most sensitive to using the alternative growth curve. This is not surprising because it changes the ages to which many of the fish are assigned; in particular, fish under 50cm tend to get assign to a younger age class. Many fish end up being assigned age 0, which we did not have using the default growth curve. As a result, the *M* estimate is very high at age 0 as opposed to age 0.5 (almost 1.5 per half year), but then close to zero at subsequent ages (with the exception of a small but strange spike at age 1.0). The *F* estimates using the alternative growth curve are for the most part substantially lower, and the population size estimates much higher (note the larger range for the y-axis).

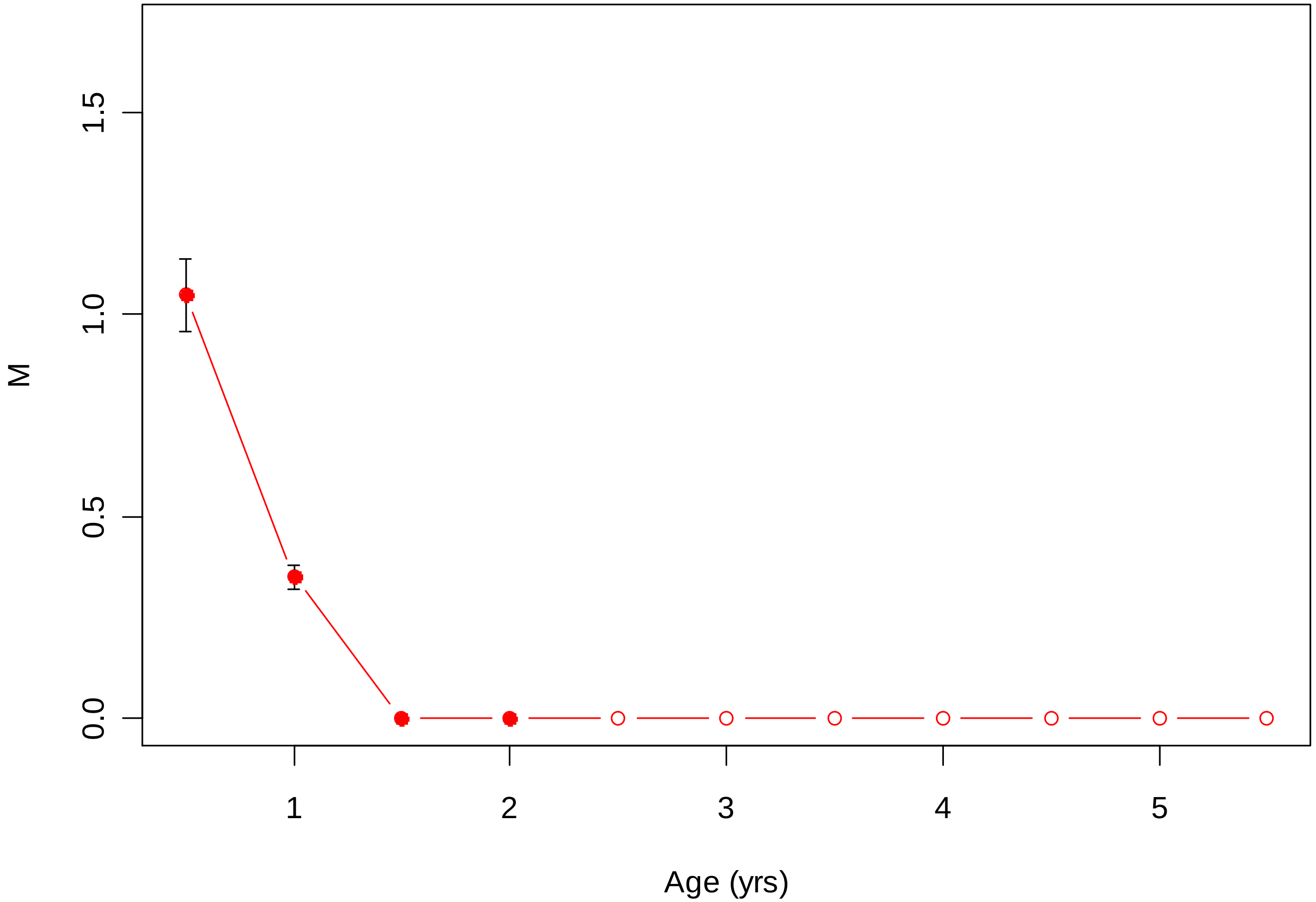
For the other alternatives, the *M* estimates are all quite similar to the base run, as are the population size estimates. In terms of the *F* estimates, they relatively insensitive to excluding catch data and to using a longer mixing period; however, there are some notable differences when the Oman releases are omitted. In particular, the *F* estimates for larger fish (ages 2.5 and above) are quite a bit higher. This is expected because the percent returns from the Oman releases, which were larger fish, was very low and, therefore, including these releases brings the overall estimate of fishing mortality down.

**Table 6.** Parameter estimates from the base model run: natural mortality rate (M) estimates by age, fishing mortality rate (F) estimates by cohort and age, and abundance at age of first tagging (P) by cohort (in millions).

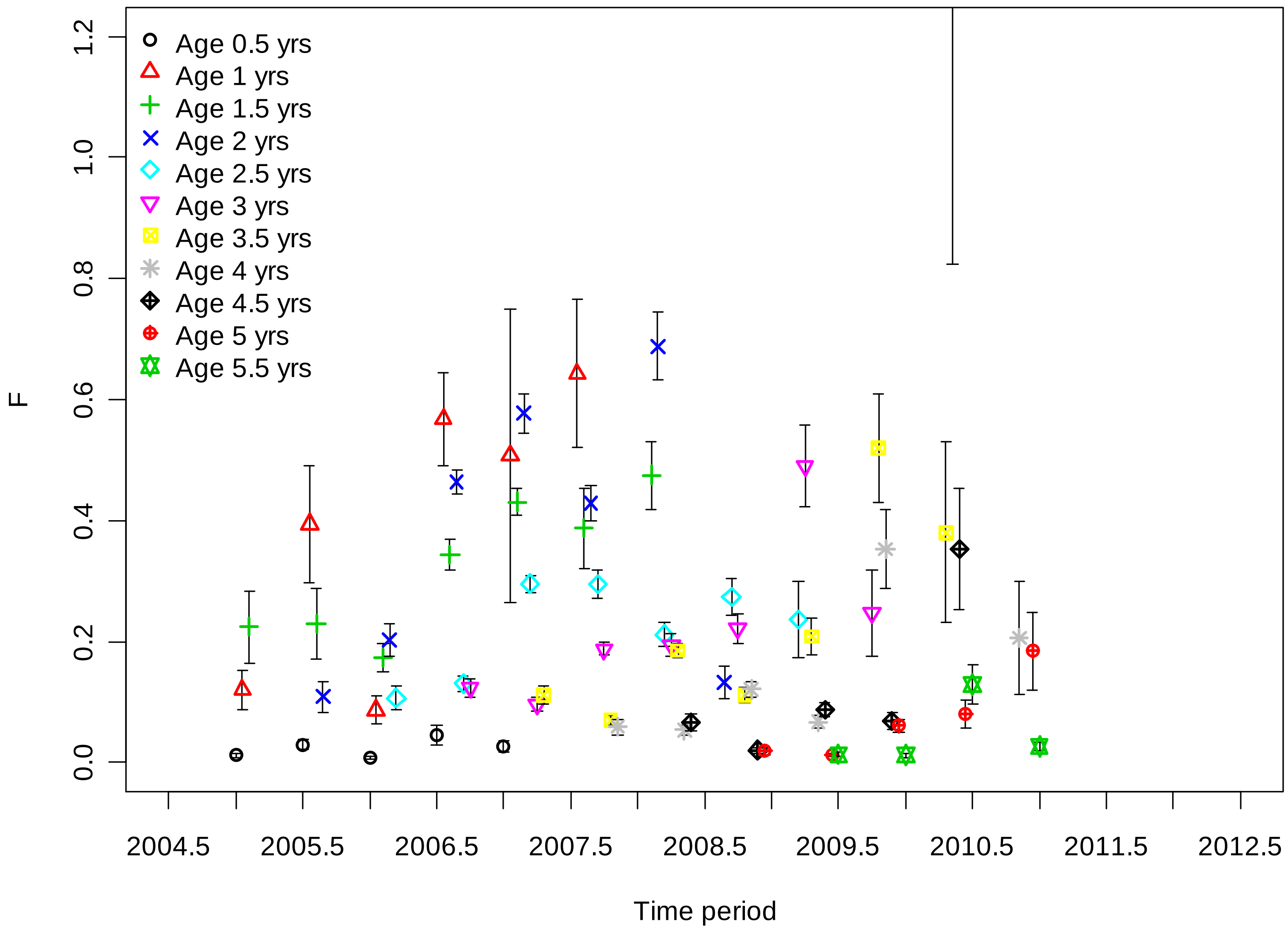
| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| M | | Age 0.5 | 1.0 | 1.5 | 2.0+ | | | | | | | |
| | | 1.05 | 0.35 | 0.00 | 0.00 | | | | | | | |
| | | | | | | | | | | | | |
| F | Cohort | Age 0.5 | 1.0 | 1.5 | 2.0 | 2.5 | 3.0 | 3.5 | 4.0 | 4.5 | 5.0 | 5.5 |
| | 2003.5 | | | 0.22 | 0.11 | 0.11 | 0.12 | 0.11 | 0.06 | 0.07 | 0.02 | 0.01 |
| | 2004.0 | | 0.12 | 0.23 | 0.20 | 0.13 | 0.10 | 0.07 | 0.05 | 0.02 | 0.01 | 0.01 |
| | 2004.5 | 0.01 | 0.39 | 0.17 | 0.46 | 0.30 | 0.19 | 0.18 | 0.12 | 0.09 | 0.06 | 0.13 |
| | 2005.0 | 0.03 | 0.09 | 0.34 | 0.58 | 0.29 | 0.19 | 0.11 | 0.07 | 0.07 | 0.08 | 0.03 |
| | 2005.5 | 0.01 | 0.57 | 0.43 | 0.43 | 0.21 | 0.22 | 0.21 | 0.35 | 0.35 | 0.18 | 0.00 |
| | 2006.0 | 0.05 | 0.51 | 0.39 | 0.69 | 0.27 | 0.49 | 0.52 | 1.29 | 2.41 | 0.00 | 0.00 |
| | 2006.5 | 0.03 | 0.64 | 0.48 | 0.13 | 0.24 | 0.25 | 0.38 | 0.21 | 0.00 | 0.00 | 0.00 |
| | | | | | | | | | | | | |
| P | Cohort: | 2003.5 | 2004.0 | 2004.5 | 2005.0 | 2005.5 | 2006.0 | 2006.5 | | | | |
| | Age: | 1.5 | 1.0 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | | | | |
| | | 51.0 | 79.8 | 60.2 | 81.9 | 54.6 | 51.2 | 62.2 | | | | |

**Figure 3.** Parameter estimates from the base model along with ± 1 standard error bars. (a) Natural mortality rate (M) estimates by age; (b) fishing mortality rate (F) estimates by cohort and age; and (c) abundance (P) by cohort (note that only P at the first age tagged is estimated directly in the model; subsequent age estimates are derived from the estimates of F and M).

(a) Natural mortality



(b) Fishing mortality



(c) Population size

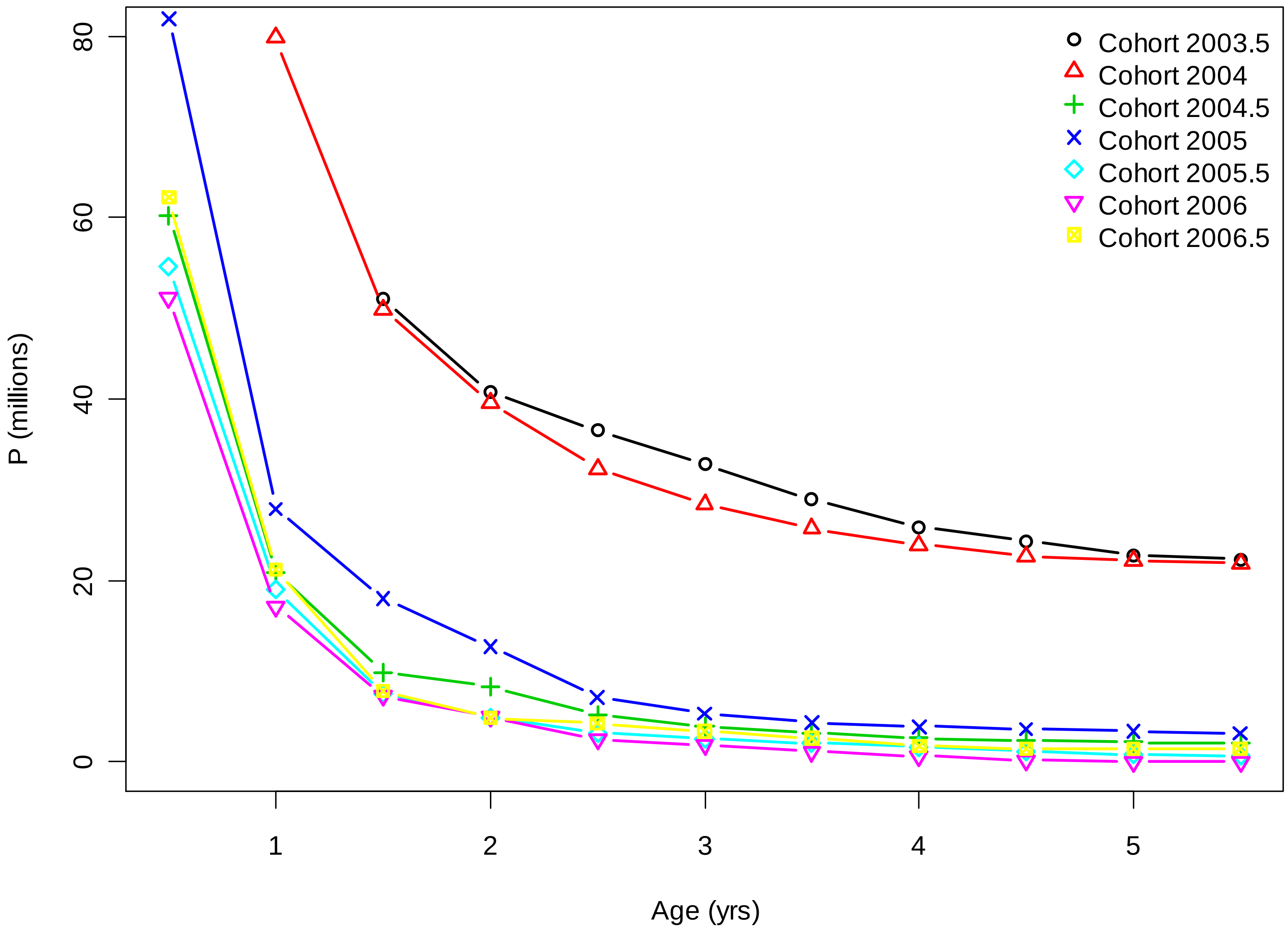
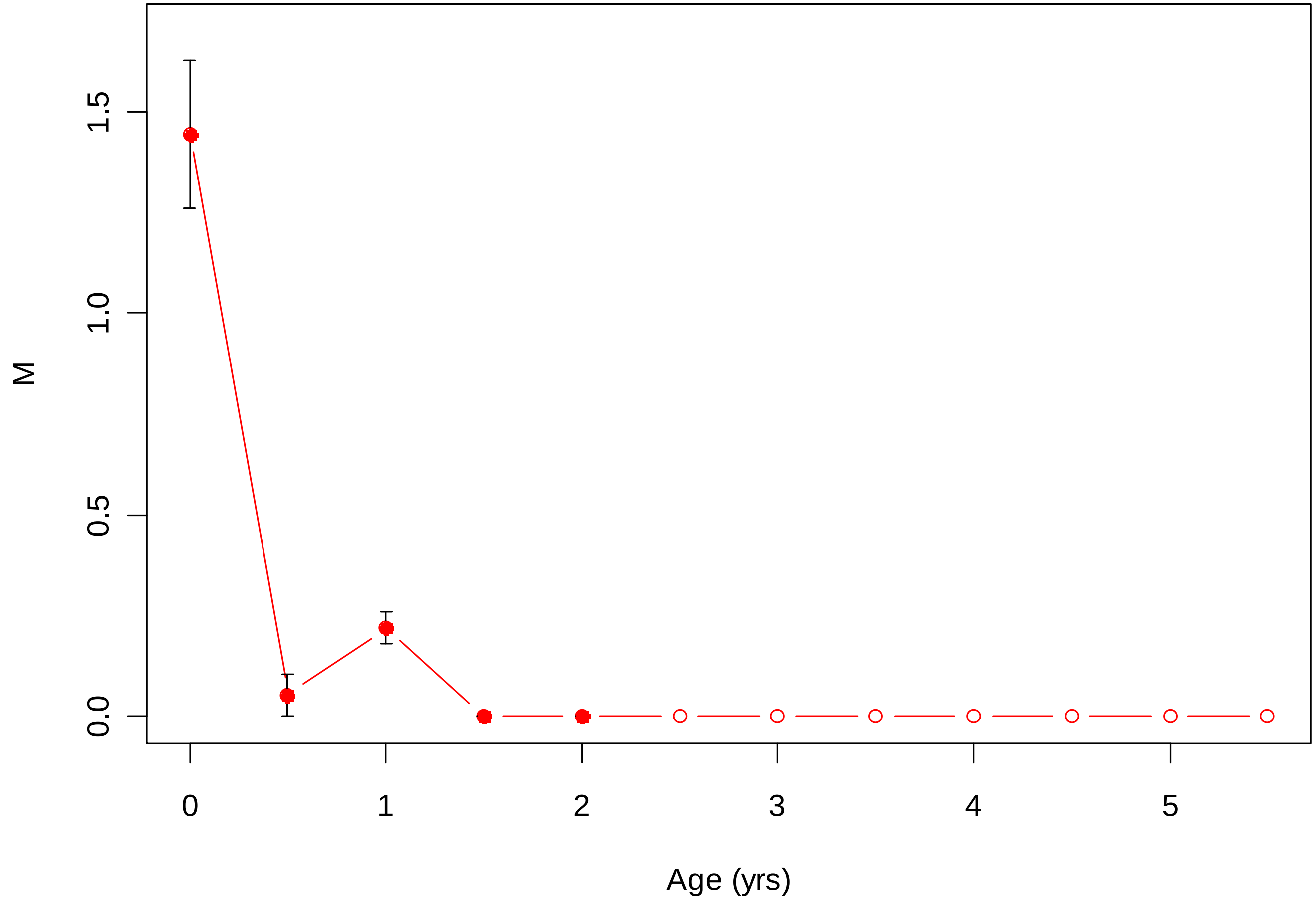
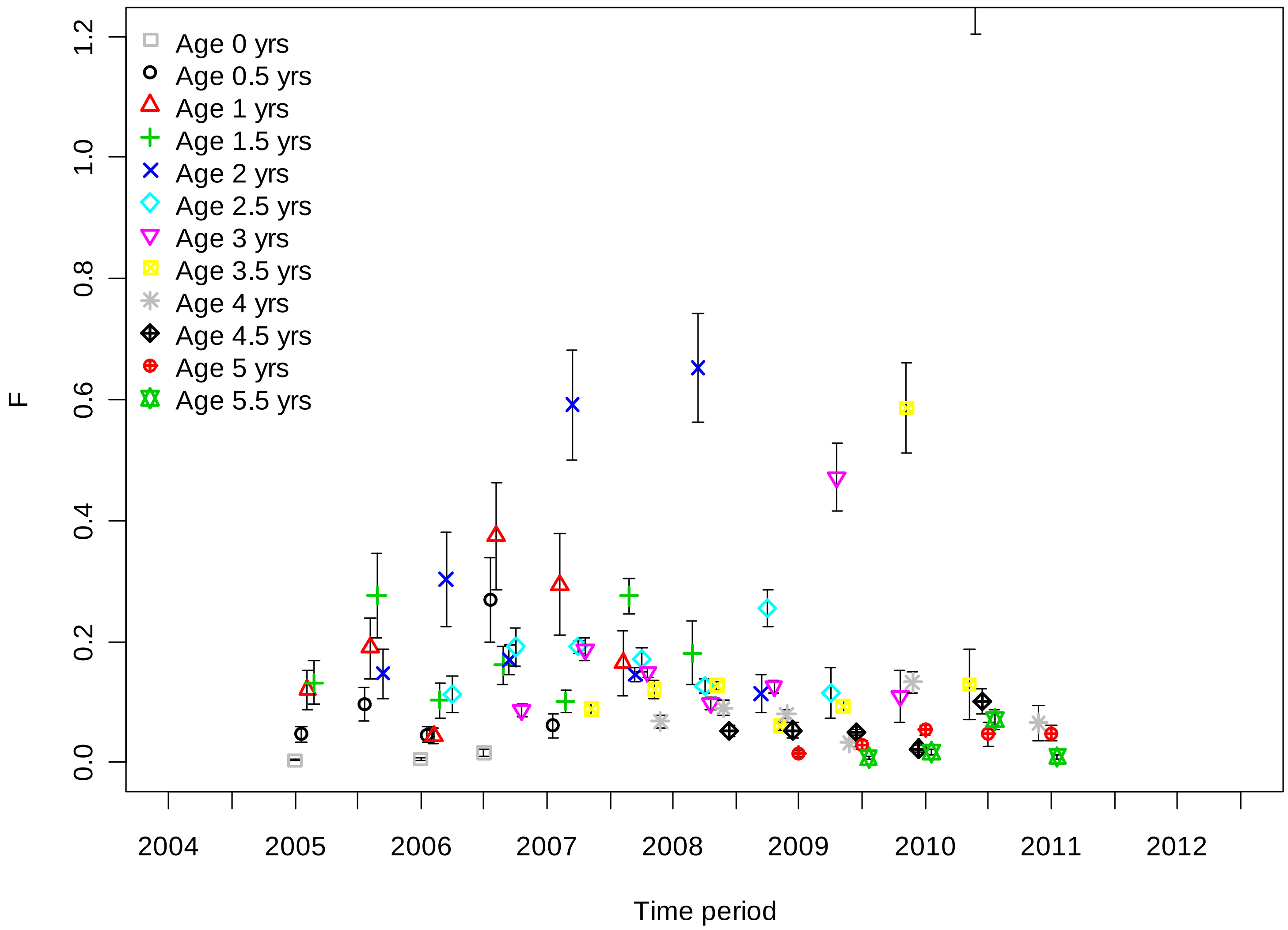


**Figure 4.** Parameter estimates from the model using the alternative growth curve along with ± 1 standard error bars. (a) Natural mortality rate (M) estimates by age; (b) fishing mortality rate (F) estimates by cohort and age; and (c) abundance (P) by cohort (note that only P at the first age tagged is estimated directly in the model; subsequent age estimates are derived from the estimates of F and M)..

(a) Natural mortality



(b) Fishing mortality



(c) Population size

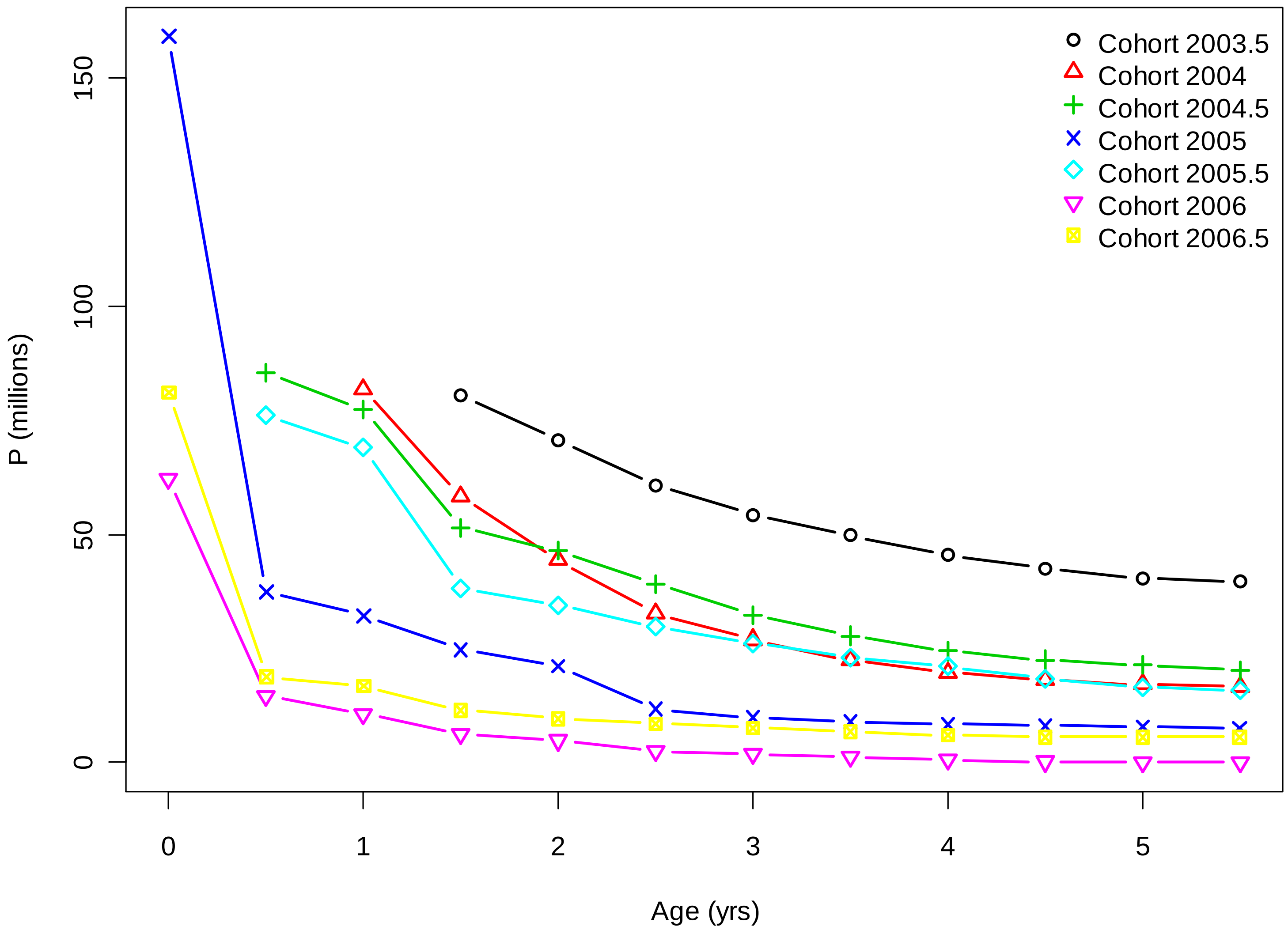
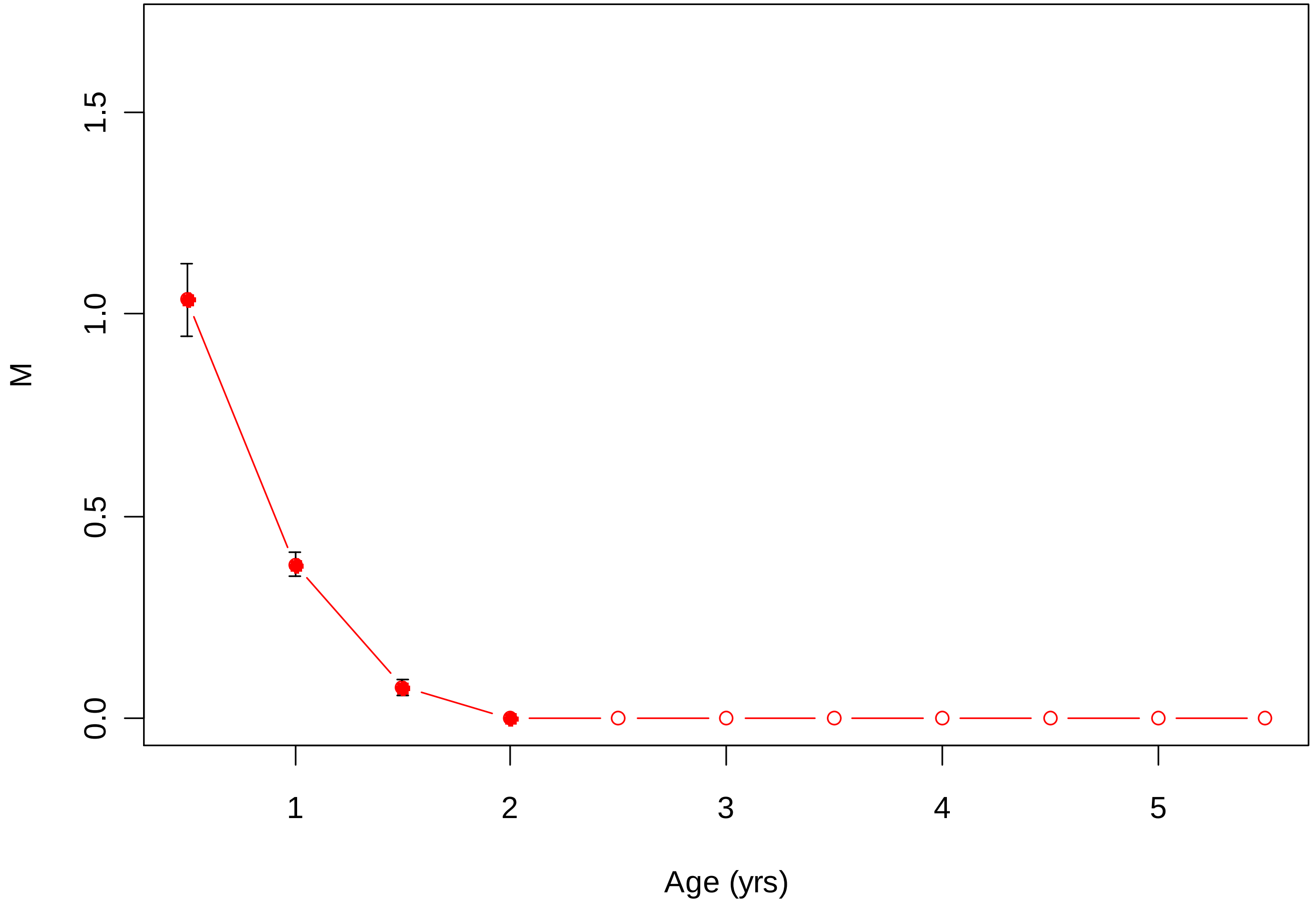
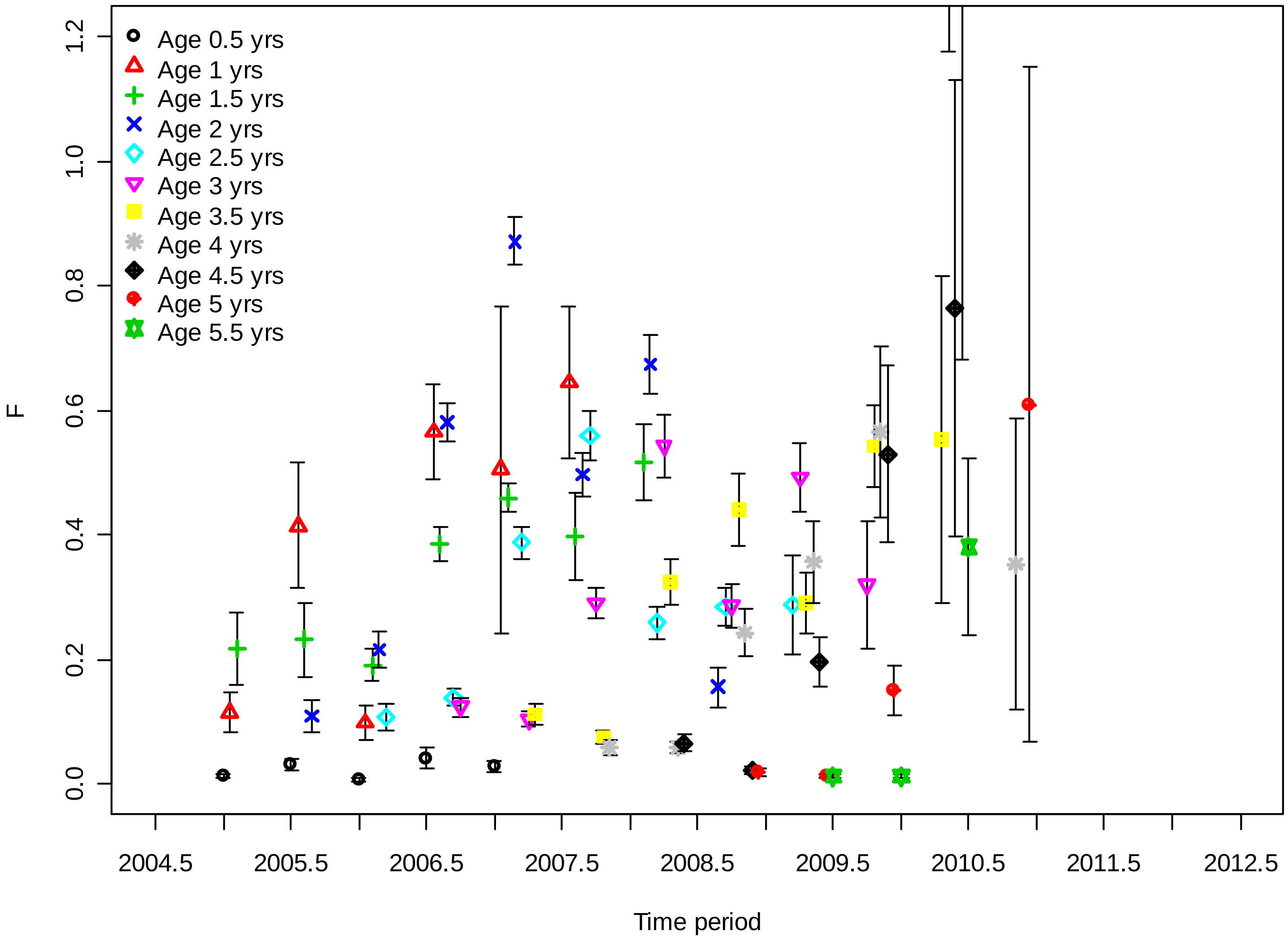


**Figure 5.** Parameter estimates from the model omitting Oman releases along with ± 1 standard error bars. (a) Natural mortality rate (M) estimates by age; (b) fishing mortality rate (F) estimates by cohort and age; and (c) abundance (P) by cohort (note that only P at the first age tagged is estimated directly in the model; subsequent age estimates are derived from the estimates of F and M)..

(a) Natural mortality



(b) Fishing mortality



(c) Population size

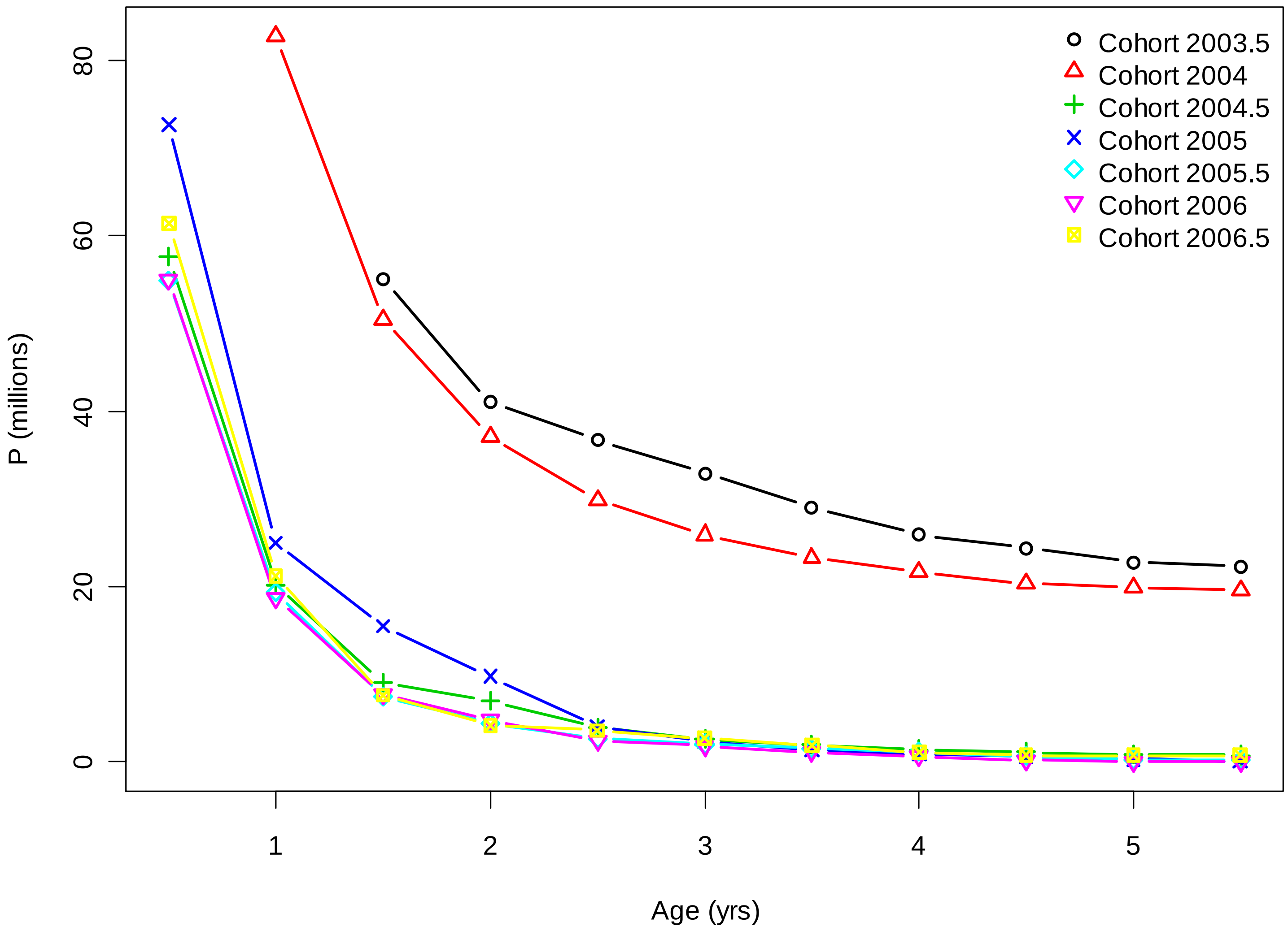
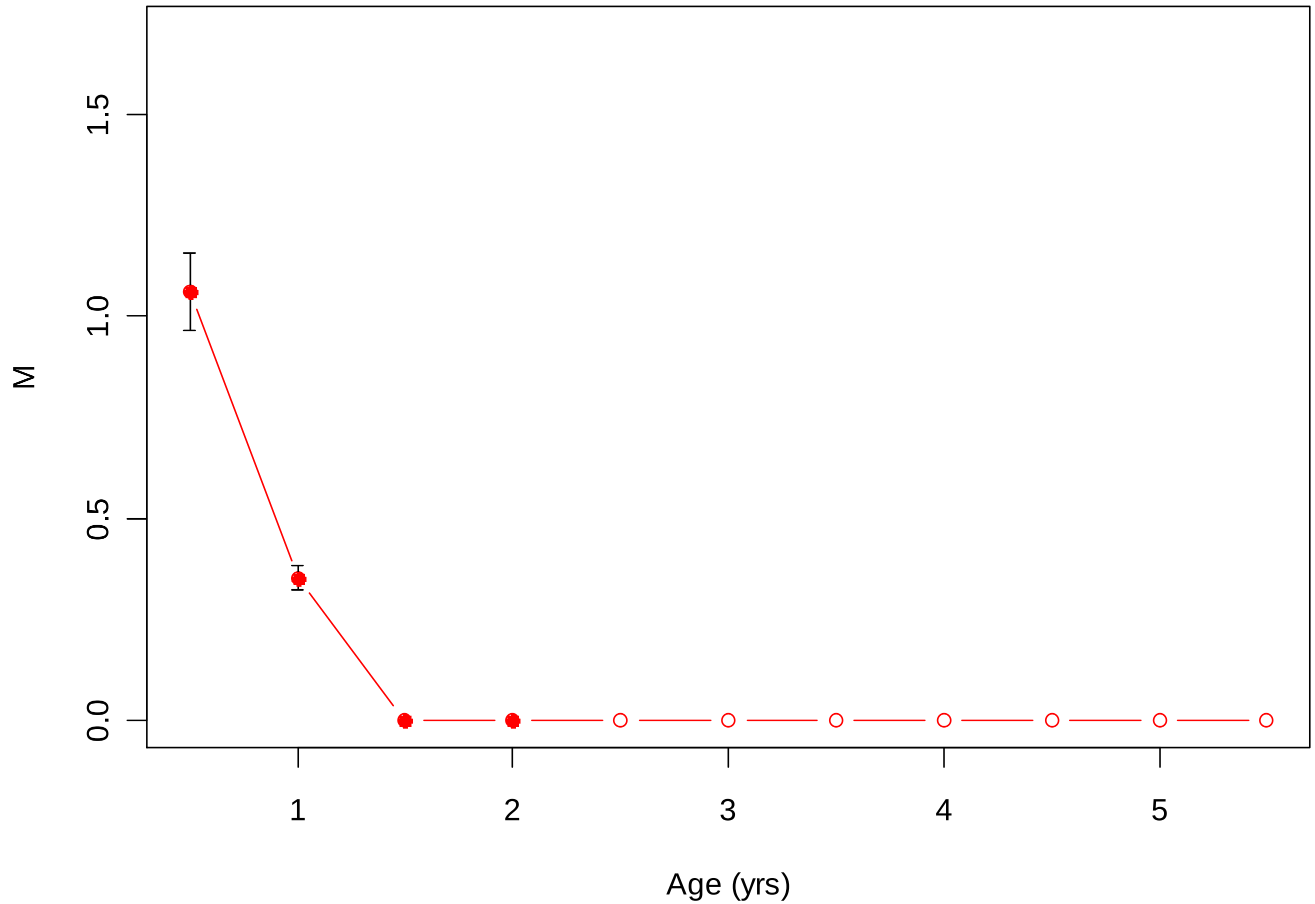


**Figure 6.** Parameter estimates from the model omitting catch data along with ± 1 standard error bars. (a) Natural mortality rate (M) estimates by age; and (b) fishing mortality rate (F) estimates by cohort and age. (Note that abundance estimates are not obtained without catch data.)

(a) Natural mortality



(b) Fishing mortality

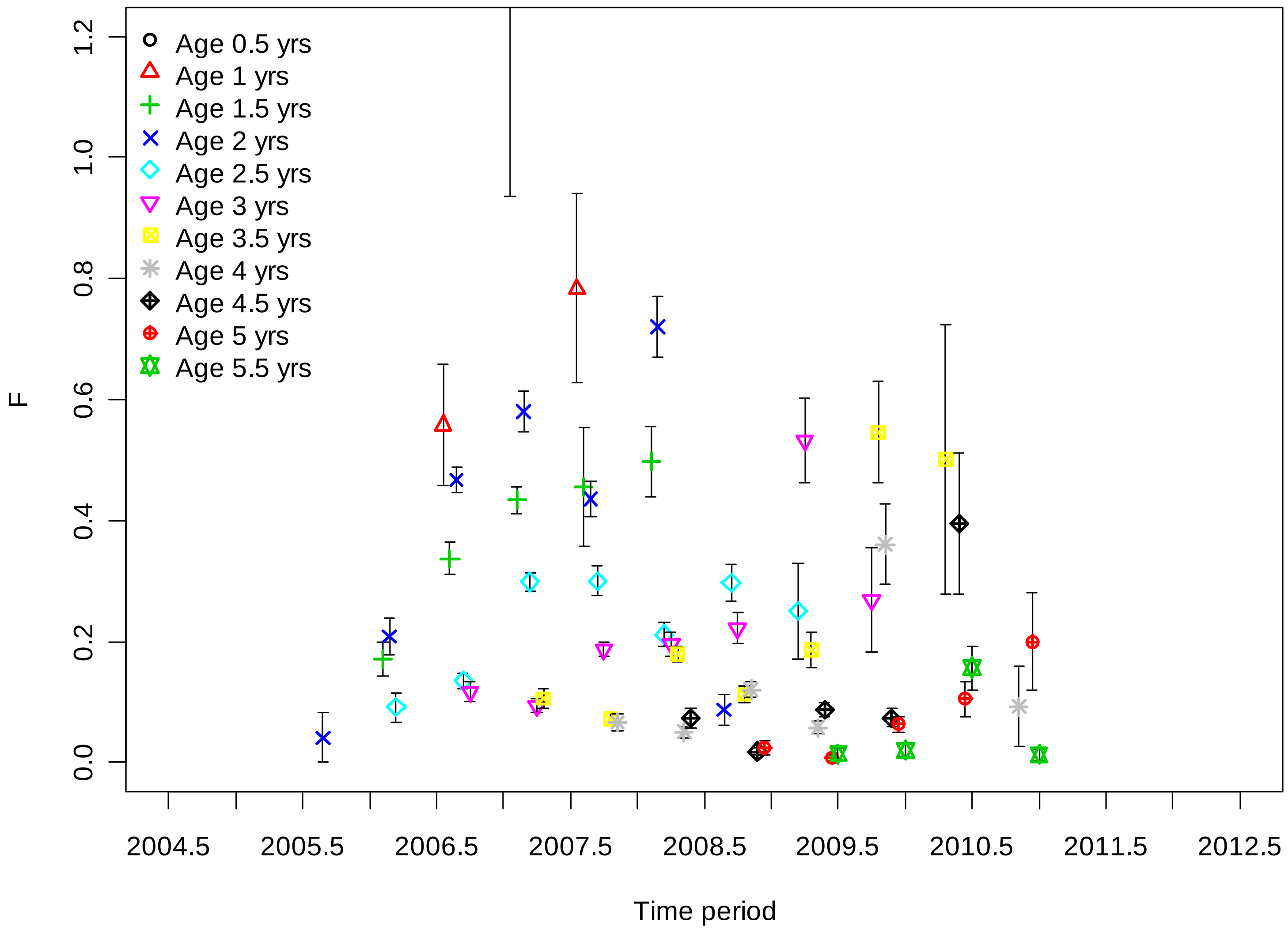
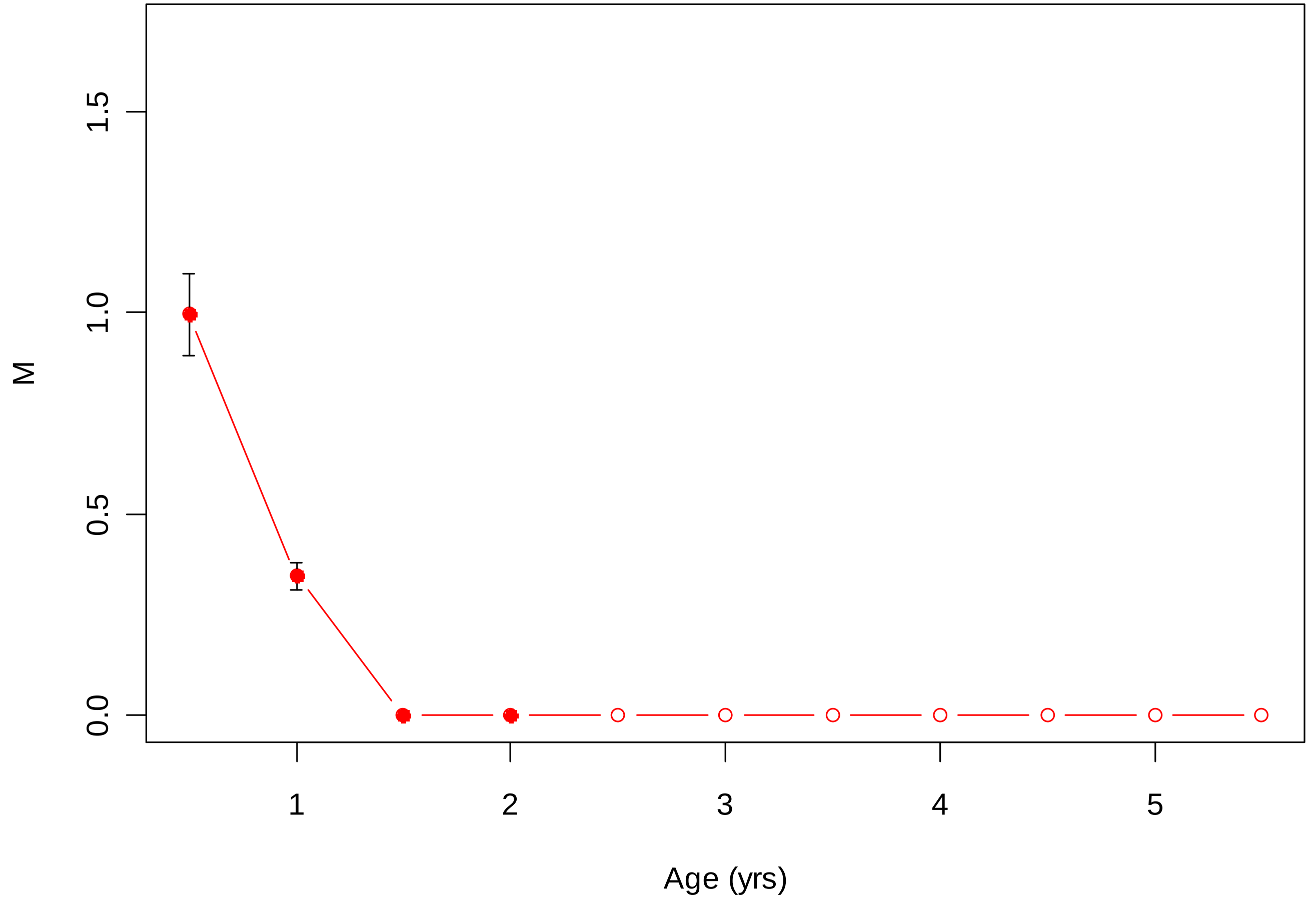
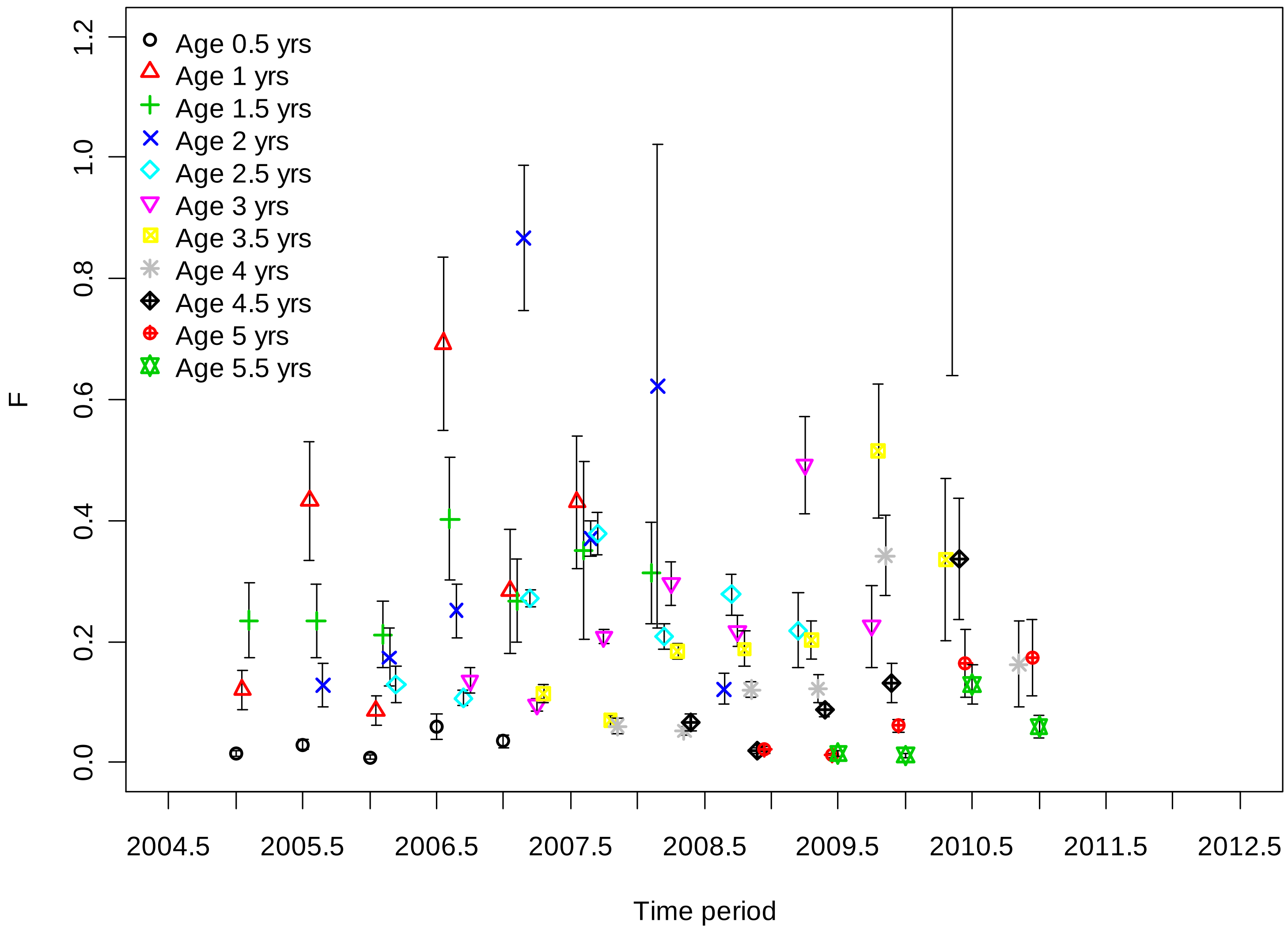


**Figure 7.** Parameter estimates from the model using a mixing period of 12 months along with ± 1 standard error bars. (a) Natural mortality rate (M) estimates by age; (b) fishing mortality rate (F) estimates by cohort and age; and (c) abundance (P) by cohort (note that only P at the first age tagged is estimated directly in the model; subsequent age estimates are derived from the estimates of F and M)..

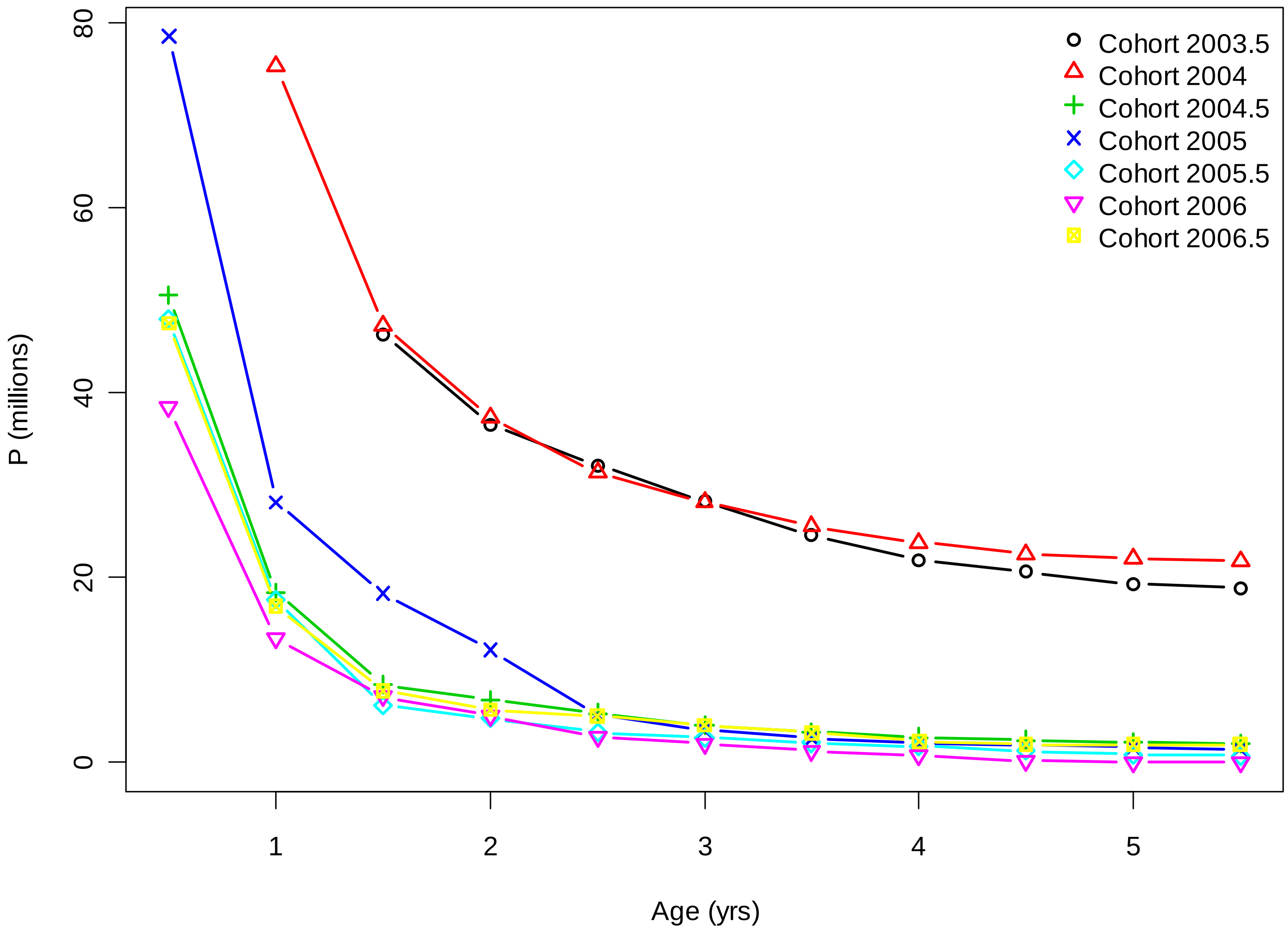
(a) Natural mortality



(b) Fishing mortality



(c) Population size



## Discussion

The results presented here provide a useful first step in estimating mortality rates and abundance from the Indian Ocean YFT tag-recapture and catch data. The estimates of natural mortality may prove particularly useful given the lack of alternative methods for estimating this parameter. Nevertheless, a large number of uncertainties exist in the data inputs and assumptions of the model, and the results must be considered carefully. For example, the most plausible growth curve for YFT has yet to be agreed upon, and as we demonstrated, the results of the BP analysis can be highly sensitive to the growth curve used. Also, the choice of a half-yearly time-step seemed most reasonable based on the data and some results obtained using annual and quarterly time-steps; however, the fact that the results could be quite different using these alternative time-steps needs to be given greater consideration (which lack of time prevented for this report).

One of the key assumptions in the non-spatial BP analysis is that full mixing occurs across the population of interest. Thus, in the results presented here, we were assuming YFT from the Western and Eastern Indian Ocean mix completely. Without more tagging in the east, and especially without reporting rates from fisheries other than the purse seine fishery, it is very difficult to know to what extent this assumption is being met. In future, it may be possible to apply a spatial version of the BP model, say using the same 5 areas as defined for the MULTIFAN-CL stock assessment. In this case, mixing only needs to occur within each area for the model assumptions to be met. However, movement rates between areas then need to be estimated, either within the model or externally and input to the model. Unfortunately, with the lack of releases in all areas and the lack of reporting rates for all fisheries, it would be very difficult to estimate reliable movement rates.

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