CCAMLR Science, Vol. 18 (2011): 29–45

ESTIMATION OF NATURAL MORTALITY FOR THE PATAGONIAN TOOTHFISH AT HEARD AND MCDONALD ISLANDS USING CATCH-AT-AGE AND AGED MARK-RECAPTURE DATA FROM THE MAIN TRAWL GROUND

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Abstract

Attempts to estimate natural mortality, as a single constant *M*, simultaneously with other model parameters in integrated assessments via CASAL for the Heard and McDonald Islands (HIMI, Division 58.5.2) Patagonian toothfish (*Dissostichus eleginoides*) fishery have been unsuccessful. An alternative strategy was adopted whereby the relatively long time series of catch-at-age and mark-recapture data from the main trawl ground at HIMI were used to estimate *M*. Catch and releases by age class for this fishery were obtained using proportions-at-length and fishery- and year-specific age–length keys (ALKs) for years 1998 to 2008. A large proportion of the recaptures of fish released in this fishery were aged and these were used to obtain recapture numbers by age class. Two alternative estimation models were programmed in R, based on alternative ordinary differential equations (ODE) for within-year population dynamics. These are the BODE model (Baranov ODE) and the CCODE model (constant catch ODE). The CCODE model is a new model for describing total mortality which disaggregates fishing and natural mortality differently to the Baranov equations and does not require a catch equation but removes catch-at-age numbers directly from the estimates of population numbers-at-age. The properties of these two models for estimation of *M* have been studied using simulation. In application to the data obtained for the HIMI main trawl fishery, the CCODE model gave a well-behaved profile for the log-likelihood with the corresponding estimate of *M* of 0.155, however, the 95% confidence bounds of the estimate were very wide ranging from 0.055 to 0.250 (based on a Poisson over-dispersion estimate of 3). In contrast, the BODE model gave unrealistic estimates of *M* and the annual fishing mortality rates.

Keywords: fishing mortality, Baranov equations, profile maximum likelihood estimation, age–length keys, CCAMLR

Introduction

The annual natural mortality rate, *M*, is a very influential parameter in determining the productivity of a stock when considered in combination with annual number of recruits, growth rate in body size and the age-at-maturity ogive.

The integrated assessments using CASAL (Bull et al., 2005) of Patagonian toothfish (*Dissostichus eleginoides*) for South Georgia (Subarea 48.3) (Hillary et al., 2006) and Heard and McDonald Islands (HIMI, Division 58.5.2) (Candy and Constable, 2008) and Antarctic toothfish (*D. mawsoni*) in the Ross Sea (Subarea 88.1) (Dunn and Hanchet, 2007) apply a fixed value of *M* of 0.13 y^{-1} rather than estimate this parameter jointly with other model parameters. The use of a fixed *M* of 0.13 y^{-1} in Hillary et al. (2006) was based on Beverton-Holt invariants. The estimate of *M* used for the Antarctic toothfish was also 0.13 y^{-1}, where this value was based on an analysis of catch-curve data from the Ross Sea fishery using the Chapman-Robson estimator (Dunn et al., 2006).

A recent update of the HIMI integrated assessment using comprehensive ageing data for the catch, but excluding length-binned mark-recapture data (applied in some of the CASAL datasets/models in Candy and Constable, 2008), also applied an M of 0.13 y^{-1}. Since then attempts to estimate M in the different datasets/models for HIMI have proved unsuccessful with a strong negative correlation between the estimate of M and the B_0 parameter, which is defined as median pre-fishery spawning stock biomass, resulting in both parameter estimates reaching bounds even when these were set unrealistically wide in each case. Note that B_0 is directly related to the parameter in CASAL, R_0 (= K_0 in Candy (2011)) which is the corresponding median pre-fishery number of age-1 recruits, for a given M and maturity-at-age ogive.

Since attempts to estimate natural mortality, as a single constant M, simultaneously with other model parameters in integrated assessments via CASAL for the HIMI Patagonian toothfish fishery have been unsuccessful, an alternative approach was adopted here. In this approach, catch-at-age and mark-recapture data were restricted to the main trawl ground in which the longest time series of catches and the great majority of releases and recaptures of tagged fish were available.

Two estimation models were applied, denoted the Baranov ordinary differential equation (BODE) and the constant catch ODE (CCODE) models by Candy (2011), (see that paper for a detailed description of the models and estimation methods) and programmed using the R software (R Development Core Team, 2006).

The estimation properties of both the BODE and CCODE models were studied using multi-cohort simulations of age-structured populations combined with multi-year catch-at-age and aged mark-recapture data by Candy (2011). These simulations aimed to realistically represent the HIMI toothfish fishery. Candy (2011) found that when all parameters were jointly estimated and selectivity was dome-shaped, there was a problem of substantial positive bias in estimation of M for both models. When sigmoidally shaped selectivity was simulated and the functional form of selectivity was correctly specified in the BODE model, both models gave close to unbiased estimates of M but the BODE model estimate was substantially more precise. However, when a minor misspecification of the functional form of selectivity was fitted, the CCODE model gave superior accuracy. In addition, Candy (2011) used simulation to investigate the effect of observational (i.e. measurement) errors in catch-at-age numbers. Using realistic levels of such observational error, albeit generated by a simplified error process, it was found that there was only a minor increase in bias and imprecision for the CCODE model of the order of 2% while no increase was detected using the 500 simulation runs for the BODE model. The levels of observational error were based in part on effective sample sizes calculated for the catch-at-age data obtained for the main trawl ground and used in the HIMI integrated assessment (Candy, 2009; Candy and Welsford, 2009).

The data used to estimate M using each of models BODE and CCODE was in part described in Candy and Constable (2008) and Candy and Welsford (2009). The data considered here was the component from the main trawl ground (Ground B) denoted as fishery f2 in both Candy and Constable (2008) and Candy and Welsford (2009). The release/recapture data for Ground B contains the longest series (1998–2009) with both releases and recaptures obtained using the same gear, and a consistently high number of releases per year compared to other intermittently fished trawl grounds. Very few of the fish released in Ground B were recaptured in other grounds, e.g. on Ground C that has had both trawl and longline releases over the above periods (Figure 1 of Candy and Constable, 2008). Therefore, only the Ground B release and recapture data were considered for this study. In order to apply the models and estimation method described in Candy (2011), the population in Ground B is assumed to be ‘closed’ in that there has been no immigration nor emigration with only the population-level processes of recruitment, ageing, natural mortality and fishing mortality assumed to have operated.

Models

The models and estimation methods are described in detail in Candy (2011). However, one modification to these models is described below.

The selectivity function fitted by the BODE model was the ‘lower-normal’ (LN) function as described in Candy (2011, equation (22)) but with the modification that fish below age 4 could be estimated to have non-zero selectivity (i.e. a_0 set to zero in equation (22)) as described by the following equation

$$S'_a = 2^{-\left[(a-\lambda)/\sigma_L\right]^2} \quad ; \; 0 < a \le \lambda$$
$$= 1 \quad ; \; a > \lambda \qquad (1)$$

where λ is a cut-point parameter corresponding to the age at which S'_a is 1, and σ_L is a parameter denoting the standard deviation of the scaled normal density function specifying the lower arm of the function.

HIMI main trawl ground data

Candy and Welsford (2009) presented summaries of the ageing data and length-frequency data used, via the application of year-specific age–length keys (ALKs), to obtain proportions of the catch by age class for each fishery modelled in the integrated assessment. The data considered here was that component of this data obtained only for the main trawl ground (Ground B). In this study the ALKs used to obtain total catch-at-age numbers were year and fishery-specific for Ground B since there were sufficient aged fish over the years 1998–2008 to calculate these ALKs without the problem of many unpopulated age by year class combinations if consideration of the tails of the age distribution is excluded.

To obtain catch numbers-at-age instead of proportions-at-age, the number of fish sampled in each of the length-frequency samples was scaled up to a total catch by dividing by the fraction the length samples represented of the estimated total catch numbers which was denoted as the number of 'scanned' fish in Candy and Constable (2008). Table 1 gives the total catch (i.e. scanned) numbers (i.e. aggregated across age classes) for each fishing season, along with the size of the random sample of fish measured for length and the sub-sample of these that were aged. Figure 1 shows the catch-at-age proportions both observed and the corresponding fitted values obtained from CASAL for Ground B trawl catches for season 2 (mid-season: 1 May–30 September) and season 3 (late-season: 1 October–30 November) as given in Candy and Welsford (2009). The legal HIMI fishery began in 1997 in Ground B (denoted fishery f2 in Candy and Constable, 2008) with the mark-recapture program beginning in April 1998 also in this ground (Candy et al., 2007). The total number of releases and recaptures for f2 up to, and including, the 2007 season are given in Figure 1 of Candy and Constable (2008).

Updating Candy and Constable (2008), the total releases up to August 2009 for Grounds B and C were 8 284 and 3 416 respectively, with trawl responsible for 2 158 of the Ground C numbers. Updated numbers of releases for the Ground B trawl fishery, where only releases from this fishery were considered, with numbers by length bin, were obtained for 1998 to 2008. Any recaptures within 60 days of release or recaptures within the same within-year season of early-season (1 December to 30 April), mid-season or late-season (Candy and Constable, 2008) as the release were removed from the number of releases and number of recaptures to allow for adequate mixing of tagged and untagged fish. This restriction gave a total over years 1998 to 2008 of 7 588 releases. Table 1 gives a summary of release numbers by fishing year and recapture numbers by years of release and fishing (i.e. recapture) year in f2.

Numbers of releases by length bin for fishery f2, given the above restrictions, were converted to numbers by age class using the same ALKs used to convert catch numbers-at-length to numbers-at-age.

Of the total recaptures in f2 across these years, including those removed by the above restriction, 1 065 were aged. The method of preparing and reading otoliths was described in Welsford et al. (2009). Excluding those removed by the above restriction, a total of 1 515 fish were recaptured and measured for length. Since the number of recaptures by year of release, year of recapture and age class were required, the 1 065 aged fish were tallied into the above three-way combination of categories and then scaled. This scaling involved multiplication by the ratio of the total number of recaptures by year of release and year of recapture for the 1 515 length-measured fish and restricted recaptures to the corresponding number for the aged sample of recaptures. Allowing for rounding error and small number of cases where either of these totals were zero, gave a total of 1 509 recaptured fish assigned to age classes used for modelling. The numbers of recaptures by year of release and recapture, totalled across age classes, are given in Table 1, while the numbers by age class totalled across years of release and recapture are given in Table 2.

The number of age classes considered in the fit included 1 to 20. Release numbers and recapture numbers in Tables 1 and 2 have not been adjusted for either tag mortality rate (i.e. proportion of released fish dying as a result of the initial capture/tagging process) or tag detection rate (i.e. proportion of tagged fish detected when recaptured) respectively.

For the mark-recapture data, the tag loss rate was assumed to be zero since each tagged fish over 400 mm total length received an intramuscular PIT tag and two T-bar tags, while the detection rate as estimated by Candy and Constable (2008) was assigned a value of 0.98. To allow for the detection rate being less than 1, the number of recaptures used in estimation were scaled up by dividing by 0.98. Since the trawl fishery operates a single vessel year-round, apart from down time due to steaming to and from the fishery and unloading/refuelling, two values of the proportion of the year fished (q; *sensu* Candy, 2011) were used which were 0.75 and 0.8. The tag-mortality rate was assumed to be 0.05 (see below), however, to investigate the sensitivity of parameter estimation to different values of this rate, rates of 0.01 and 0.10 were also tested. Tag-mortality rate was incorporated by multiplying the number of releases-at-age by (1-rate).

Point estimates for M were obtained jointly with other parameters by minimisation of the –2 log-likelihood value (L) to give maximum likelihood estimates (MLEs) and for comparison by profiling across a grid of values for M while estimating other model parameters simultaneously by minimisation of L giving a profile maximum likelihood estimate (PMLE) of M (Candy, 2011). The general optimisation function, `nlminb`, in R was used to minimise L. The maximum number of iterations in `nlminb` was set to 150, while convergence tolerance parameters `rel.tol` and `x.tol` were set to 0.0001 and 0.001 respectively. Since `nlminb` does not provide a Hessian matrix to calculate approximate standard errors of parameters, the PMLE approach was used to give approximate 95% confidence bounds for M (Candy, 2011).

Results

Figure 2 shows the –2 log-likelihood value (L) for the profile values of M and the loess smoothed curve (R-function `loess`) fitted to the values of L obtained from fit of the BODE model with the equation for the –2 log-likelihood given in Candy (2011). A tag-mortality rate of 0.05 was applied. The PMLE reached the upper bound of 0.30 (Table 3) and all joint minimisations of L for profiled values of M failed to converge. The joint minimisation of L with respect to all parameters also failed to converge, and at the 150th iteration gave an estimate of M of 0.209 (Table 3). The mean of the year-class strength (YCS) parameter estimates was 0.9970. The values for F corresponding to the MLE of M are given in Table 4. The corresponding selectivity parameter estimates of σ_L and λ obtained were 4.95 and 8.04 respectively, with Figure 3 showing the fitted selectivity function. The estimate of R_0 was 5 473 208 (Table 3) while the estimate of σ_C reached its upper bound of 2.0. The estimated value of F for 2001 and 2008 reached its upper and lower bound respectively. Clearly, the estimates of F for these years, and the fact that most of the catch is predicted to be taken in 2001, indicate that predictions from the BODE model diverge widely from the actual total catch-at-age numbers which are relatively stable over the 11 fishing years modelled (Table 1).

Figure 4 shows the –2 log-likelihood value (L) for the profile values of M along with the loess smoothed curve (R-function `loess`), as well as a quadratic regression, each fitted to the values of L from the fit of the CCODE model assuming a q of 0.75 and tag mortality rate of 0.05. All joint minimisations of L for profiled values of M successfully converged. Figure 4 also shows approximate 95% confidence bounds (dashed lines) for M for the case of: (i) an assumed over-dispersion parameter of 1 (i.e. no over-dispersion) for the assumed Poisson distribution for number of recaptures-at-age; and (ii) the estimated over-dispersion parameter of 3 (as described below). The PMLE for M obtained from the loess fitted curve was 0.155 with corresponding minimum value of L of –5 938 (Table 3). The mean of the estimated YCS parameters was 0.9998. The joint minimisation of L like the BODE model failed to converge. The linear correlation between profiled values of M and corresponding estimates of R_0 was high at 0.97 and this relationship was close to linear (graph not shown). This could explain the lack of strict convergence when these parameters were simultaneously estimated.

Figure 5 shows the estimated YCS parameters for the PMLE for M of 0.155. Table 4 shows values of F 'recovered' from the fit of the CCODE model using this PMLE estimate and calculated by dividing $\sum_a C_{y_i,a}$ by $\sum_a N_{y_i,a}$, where $C_{y_i,a}$

is the number of fish in the catch and $N_{y_i,a}$ the predicted number of fish in the population of age class a in year y_i (Candy, 2011). This was done to allow comparison with estimates from the BODE model. The F's are not estimated in the CCODE model but from Table 4 it can be seen that, unlike for the BODE model, the recovered values are realistic and stable across years. Figure 6 shows the observed and expected (i.e. predicted) number of recaptures across years and age classes, showing the 1:1 (solid) line and the best fitting Poisson generalised linear model (GLM) with identity link to give a regression line (dashed) fitted through the origin. This fitted line demonstrates how well the observed and expected numbers of recaptures correspond on average as the fitted line is indiscernible from the 1:1 line.

Figure 7 shows the same observed and expected number of recaptures as Figure 6 but displayed as age frequencies within each fishing year. For an M of 0.155, the expected number of recaptures fitted the observed numbers reasonably well in all years (Figure 7).

Figure 8 shows the estimated linear regression between residual variance and mean expected number of recaptures for binned values using bin classes for expected number of recaptures of 8 units between 0 and 24 with upper bin >24. The residual variance was calculated as the variance of observed minus expected number of recaptures for values in the each bin. A gamma GLM with identity link weighted by the number of residuals in each bin minus 1 was fitted through the origin and the slope of the regression gives an estimate of the over-dispersion parameter. The variance and corresponding mean for the 0–8 bin was excluded because this bin's mean expected number of recaptures was close to zero which, when combined with its high leverage and weight, greatly exaggerates its influence on the fitted line. Comparison of the 1:1 line (solid line) in Figure 8, which represents Poisson variation, compared to the regression line indicates over-dispersion relative to a Poisson for the remaining bins. The estimate of the over-dispersion parameter (i.e. the slope of the regression) was 3.05 (SE = 0.72). This estimate multiplied by the critical value for 95% probability level of a chi-square distribution with a single degree of freedom of 3.84 was used to obtain an approximate 95% confidence bound for the estimate of M to give lower and upper bounds of 0.055 and 0.250 respectively (as shown graphically in Figure 4 as the range of M defined by the ends of the upper dashed line), representing in percentage terms bounds of –65% and 61%. When the over-dispersion was assumed to be 1, these bounds (shown as the lower dashed line in Figure 4) were 0.095 and 0.210 corresponding to percentage bounds of –39% and 35%. When the observed and expected recaptures for 2006 to 2008 were excluded, the result is shown in Figure 9 with the GLM refitted, however, the CODE model was not refitted to this reduced dataset. Figure 10 shows the recalculated variances by bin and the refitted gamma GLM, with the over-dispersion parameter re-estimated to be 2.15 (SE = 0.16).

A number of sensitivity tests were each independently applied to the above estimation of the CCODE model to investigate the effect on the MLE of M where: (i) tag mortality rate was reduced from 0.05 to 0.01; (ii) tag mortality rate was increased from 0.05 to 0.10; and (iii) q was increased from 0.75 to 0.80. The results are shown in Table 3.

When tag mortality rate was reduced from 0.05 to 0.01, the MLE of M was 0.154 with a corresponding estimate of R_0 of 6 415 796. When tag mortality rate was increased from 0.05 to 0.10, the MLE of M was 0.155 with a corresponding estimate of R_0 of 3 964 137. Reducing the tag mortality rate increases the number of 'effective' releases and thus increases the number of tagged fish at liberty so that if number of recaptures is kept constant, then a simple Petersen estimate (Seber, 1982) for population size gives a correspondingly higher estimate of size which, given a fixed M and fixed catches, results in a higher value for R_0. The converse is true when tag mortality rate is increased so that R_0 should decrease. The above results in terms of estimates of R_0 correspond with this theory.

Table 3 gives results when the fraction of the year fished, q, was increased from 0.75 to 0.80 with a similar value for the MLE of M compared to that obtained when q was set to 0.75.

The BODE model was also fitted using the dome-shaped 'double-normal' (DN) selectivity function described in Candy (2011) by equation (21) but with a_0 set to zero in the same way equation (1) above was obtained. However, the same problems occurred as those described above when the BODE model was fitted using LN selectivity (equation (1)). Therefore further detailed results are not presented for this version of the fitted BODE model.

Discussion

For the HIMI data from Ground B, the CCODE model was reasonably successful in estimating *M* as seen by the fit to the number of recaptures shown in Figures 6 and 7. The profile –2 log-likelihood graph (*L*) (Figure 4) indicates that profile maximum estimation is well-behaved, giving a quadratic trend with only a small degree of oscillation of values of *L* about the smooth (loess) curve shown. Estimation for the BODE model was poorly behaved in this regard, as seen in Figure 2. For a given *M*, slight variations in the estimate of R_0 (obtained by back-transforming the estimate obtained on the log scale) can produce large differences in the population age structure at the commencement of fishing. This is compounded by the property of the estimates that the earlier pre-fishery YCS estimates tend to 1 since their actual values cannot be estimated due to lack of information in the data (Figure 5).

For the BODE model, apart from the fitted selectivity function, the estimates of the *F*'s (Table 4) are unrealistic. The estimate of R_0 for the CCODE model appears to be of a reasonable order of magnitude at 5.6 million, assuming recruits to the main trawl ground (f2) are drawn from the wider HIMI plateau area since the estimates of this parameter for the entire stock at HIMI were found to be in the range 2.8 to 4.5 million by Candy and Constable (2008), depending on the datasets and/or data weightings used in the integrated assessment. More recently when mark-recapture data were not used and catch-at-length data were replaced by catch-at-age data, this range was 4.2 to 4.5 million (Candy and Welsford, 2009). Also the fit to the number of recaptures-at-age was superior using the CCODE model with a substantially lower –2 log-likelihood component for the mark-recapture data (–5 938) compared to the BODE model (–5 829), although the degree of over-dispersion in both cases was large (Figure 8). The over-dispersion estimate was considerably smaller when the data from 2006 and later were removed from observed and expected recaptures (Figures 9 and 10). Table 1 shows that for 2006 and 2008, the total number of recaptures is considerably lower than for the other years. The reasons for this are unclear and examination of detection probabilities showed that these were very similar across years so that changes in detection rate could not be the cause.

The results indicate that there is not sufficient information in the HIMI recapture numbers-at-age to simultaneously estimate *M* and R_0 as indicated by the very high positive correlation between these two parameters. However, the profile likelihood method of estimation, which does not simultaneously estimate these two parameters, gave a clear optimum value for *M* when the CCODE model was fitted with a well-behaved profile shape, and joint minimisations with respect to the non-*M* parameters that converged satisfactorily for each profiled value of *M*.

Candy et al. (2010) attempted to rectify the poor performance of the BODE model, in particular its poor fit to the catch-at-age data described above, by constraining the predicted total catch (i.e. summed across age classes) to equal the actual total catch using a multinomial distribution for catch-at-age proportions along with two methods of applying an effective sample size. The estimation for these versions of the BODE model performed more poorly in terms of realistic parameter estimates for *M* and the *F*'s than the model without these constraints. In contrast, the study of Candy (2011) gave a strong suggestion of why the BODE model performed so poorly. He demonstrated that the BODE model performs very poorly in simulations when dome-shaped selectivity, as modelled using the DN selectivity function, was simulated and fitted. The performance was poorer again when LN selectivity was fitted to data simulated using DN selectivity. However, the BODE model performed well in that study given sigmoidal (LN) selectivity was simulated and correctly specified in the fit. The CCODE model also gave positively biased estimates of *M* when the same DN selectivity was simulated but gave less absolute bias, substantially greater precision, and a much better-behaved profile likelihood than the BODE model (Candy, 2011). If the selectivity for Ground B is dome-shaped, this would explain the poor performance of the BODE model. The CCODE model, for a nominal *M* in the simulations of 0.13 and with the DN selectivity applied, gave a mean estimate of *M* of around 0.15. If the selectivity in Ground B is similar to that simulated by the DN function in Candy (2011), then it could be expected that the estimate obtained for Ground B could be an over-estimate. Candy and Constable (2008) and Candy and Welsford (2009) fit such a DN selectivity function to Ground B but in these cases selectivity is in reference to population numbers-at-age for the entire HIMI fishery not just that for the Ground B trawl fishery.

The YCS estimates shown in Figure 5 indicate a very large pre-fishery cohort that was age 1 in 1987. The subsequent years until 2002 showed a stable recruitment series with a decline occurring between 2003 and 2006, followed by an increase in 2007. Other series of estimated YCS for the overall HIMI fishery are given in Candy and Constable (2008) and Candy and Welsford (2009) which both showed substantial variation in the 1990s. While it is difficult to verify if the YCS series in Figure 5 is reasonable, there is evidence for the very large 1987 year class. Taking the 1987 year class in Figure 5, these fish would have been age 12 in 1998. Figure 1, showing catch proportions-at-age for the main trawl ground for season 2 (1 May–30 September) and season 3 (1 October–30 November), indicates a clearly detectable spike in the proportion of fish caught in 1998 that were age 11 or 12 in each of season 2 and 3 (season 1 was not fished in 1998). These spikes appear to represent the remnant of the age-1 recruits from 1987 in the catch. Considering natural mortality alone, the very strong 1987 year class would be reduced to a surviving proportion of $(1 - 0.155)^{11} = 0.157$ by 1998. The fact that the spikes are so strong compared to proportions in these age classes in years after 1999 suggests that such a strong YCS of approximately 5 is quite feasible. This cohort is not seen so strongly in later fishing years, most probably for a combination of the following reasons: (i) it has died out through natural mortality; (ii) it has been fished out; and (iii) it has been subject to some emigration out of the fishery.

Despite some limitations, the CCODE model has given a reasonable estimate of M. However, its approximate 95% confidence bounds are wide, at 0.055 to 0.250, due to the high degree of over-dispersion in the recapture numbers-at-age. However, it should be noted that the estimate of R_0 was sensitive to the assumed value of tagging-induced mortality rate and from the profiled estimates of M, it was found that these two estimates were highly correlated. Similarly, M would be sensitive to the values used for tag-loss rate and tag-detection rate. However, unlike the tagging-induced mortality rate, both these parameters have been estimated or had their value inferred with a reasonably high degree of certainty. The issue of tag-mortality rate is difficult to resolve, since it is not possible to gather direct observations on this mortality rate for all released fish. Agnew et al. (2006) carried out a study to estimate post-tagging survival for *D. eleginoides* caught by longline in Subarea 48.3 by observing fish in tanks for a period after capture. They obtained an estimate of survival of 0.90 which gives a mortality rate of 0.10. A lower tag-mortality rate may be expected for fish that are released from trawl gear due to their relatively brief interaction with the fishing gear, as opposed to longline-caught fish that may have been hooked for several hours. Candidate fish for release in the HIMI fishery tagging program are carefully monitored in holding tanks for a number of hours for any signs that they are injured or moribund, and only lively uninjured fish are released. Further, only fish greater than 400 mm are tagged with PIT tags so that inserting the tags causes minimal injury to the fish. Therefore, a lower rate of tagging-induced mortality of 0.05 compared to that obtained by Agnew et al. (2006) was thought reasonable.

Candy and Constable (2008) report estimates of substantially illegal, unreported and unregulated (IUU) catches prior to 2005. Estimates of numbers of catch-at-age and numbers of recaptures for these IUU removals have not been included in the estimation of M using the Ground B data. However, since all IUU removals are taken by longlining and given that, from 1997 on, for the most part of each year legal trawl operations were carried out (which acts as a deterrent to IUU fishing), it has reasonably been assumed that IUU fishing occurred predominately well outside the main trawl ground. This provides additional support to the approach taken of only considering catch and release/recaptures that have taken place in the main trawl ground for estimation of M for Division 58.5.2.

Conclusions

In application to the data obtained for the HIMI main trawl fishery, the CCODE model, gave a well-behaved profile for the log-likelihood with the corresponding estimate of M of 0.155, however, the 95% confidence bounds of the estimate were very wide ranging from 0.055 to 0.250 (based on a Poisson over-dispersion estimate of 3). Nevertheless, for the first time for this fishery a realistic estimate of M has been obtained. In contrast, the BODE model gave unrealistic estimates of M and the annual fishing mortality rates. The YCS estimates from the CCODE model indicated a very strong cohort that was age 1 in 1987 with the remnants of this cohort detected in catch-at-age proportions.

Acknowledgements

Thanks are due to Troy Robertson for assistance in preparing the data and Gabrielle Nowara for advice on otolith preparation and reading. The constructive reviews of this manuscript by Dr Richard Hillary, Prof. Doug Butterworth, Dr Philippe Ziegler and Mr John McKinlay are appreciated. Thanks are also due to the fisheries observers from the Australian Fisheries Management Authority for carrying out the tag-recapture program with support of Austral Fisheries Pty Ltd and Petuna Sealord Pty Ltd. Funding for ageing otoliths from samples taken from the catch was provided by the Fisheries Research Development Authority (FRDC project 2008/046), while funding for ageing the otoliths from the mark-recapture program was provided by Austral Fisheries Pty Ltd and Petuna Sealord Pty Ltd. Finally, the work of Dick Williams in setting up and maintaining the tagging program in previous years is gratefully acknowledged.

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Table 1: Summary of catch and tagging data for trawl ground B (f2) used in the fit.

Year of release:	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	Total
Number caught:	1 029 176	986 265	1 042 390	918 952	568 479	858 025	666 715	543 895	579 516	722 239	665 438	8 581 076
LF[1] sample size:	8 328	13 932	19 095	22 561	14 036	17 420	16 707	11 571	11 540	12 967	10 459	158 616
Aged sample size:	90	559	725	787	673	420	327	287	302	234	43	4 447
Number released[2]:	531	657	684	798	811	762	891	382	988	746	338	7 588
Year of recapture	Number recaptured[2]											
1998	0											0
1999	45	5										50
2000	22	69	47									138
2001	6	19	78	73								176
2002	1	0	8	54	81							144
2003	0	1	4	34	124	72						235
2004	1	1	3	10	72	81	109					236
2005	0	0	0	0	0	18	97	13				138
2006	0	0	0	0	0	6	5	26	37			75
2007	0	0	0	0	0	1	2	6	137	89		235
2008	0	0	0	0	0	0	1	0	18	56	7	82
Total recaptures	75	95	140	171	247	178	214	45	192	145	7	1 509

1 Random sample of lengths measured from the catch.
2 Number of tags released and recaptured excludes tags for which recaptures occurred within the same fishing season (early, mid, late) as that of the release for the same year of release and/or those recaptured within 60 days of the release date.

Table 2: Summary of catch and tagging data by age class for trawl ground B (f2) used in the fit.

Age class (years)	Number caught	Number released	Number recaptured	Age class (years)	Number caught	Number released	Number recaptured
1	15 145	12	2	14	52 498	49	4
2	96 796	99	9	15	28 313	25	0
3	380 801	307	52	16	19 244	13	1
4	888 750	715	120	17	10 384	4	0
5	1 175 669	945	157	18	7 447	1	0
6	1 503 037	1 248	223	19	6 034	1	0
7	1 365 179	1 255	321	20	4 656	0	0
8	1 033 440	1 034	233	21	3 617	1	0
9	778 479	757	174	22	2 608	0	0
10	517 100	526	119	23	1 407	0	0
11	371 552	338	63	24	2 818	0	0
12	240 029	179	15	25	525	0	0
13	74 635	79	16	26	913	0	0

Table 3: Estimates of M and other outputs from the fit of the BODE and CCODE models.

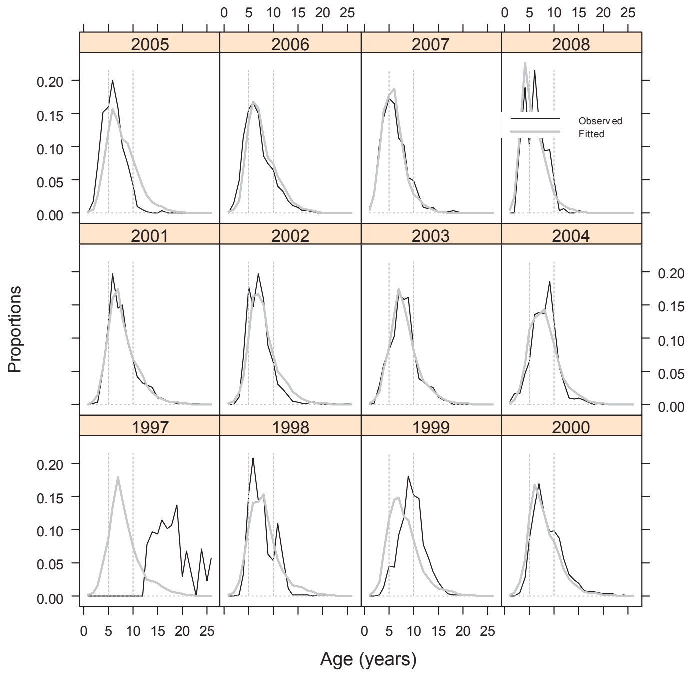
Model	Tag mortality rate	q	Estimate of M		–2 log-likelihood for number of recaptures		MLE of R_0
			MLE	PMLE	MLE	PMLE	
BODE	0.05	-	0.209	0.30[a]	–5 829	-	5 437 208
CCODE	0.05	0.75	0.144	0.155	–5 911	–5 938	5 570 500[b]
CCODE	0.01	0.75	0.154		–5 923		6 415 796
CCODE	0.10	0.75	0.155		–5 913		3 964 137
CCODE	0.05	0.80	0.145		–5 927		4 611 913

[a] Upper bound for parameter.
[b] Estimate corresponding to PMLE of M.

Table 4: Comparison of *F* estimated by BODE model and calculated from output of the CCODE model.

Year of release	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
F-estimate BODE model	0.0061	0.0081	0.0281	0.1500	0.0078	0.0081	0.0075	0.0057	0.0029	0.0065	0.0010
F-value CCODE model	0.0279	0.0289	0.0320	0.0299	0.0186	0.0280	0.0232	0.0199	0.0240	0.0360	0.0331

(a)



(b)

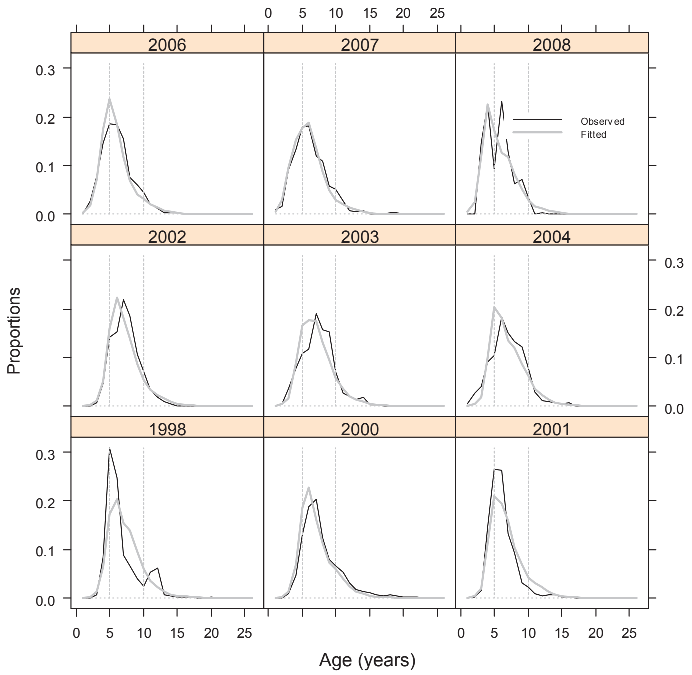


Figure 1: Catch-at-age proportions observed and fitted by CASAL for Ground B in (a) season 2 (1 May–30 September) and (b) season 3 (1 October–30 November) from Candy and Welsford (2009).

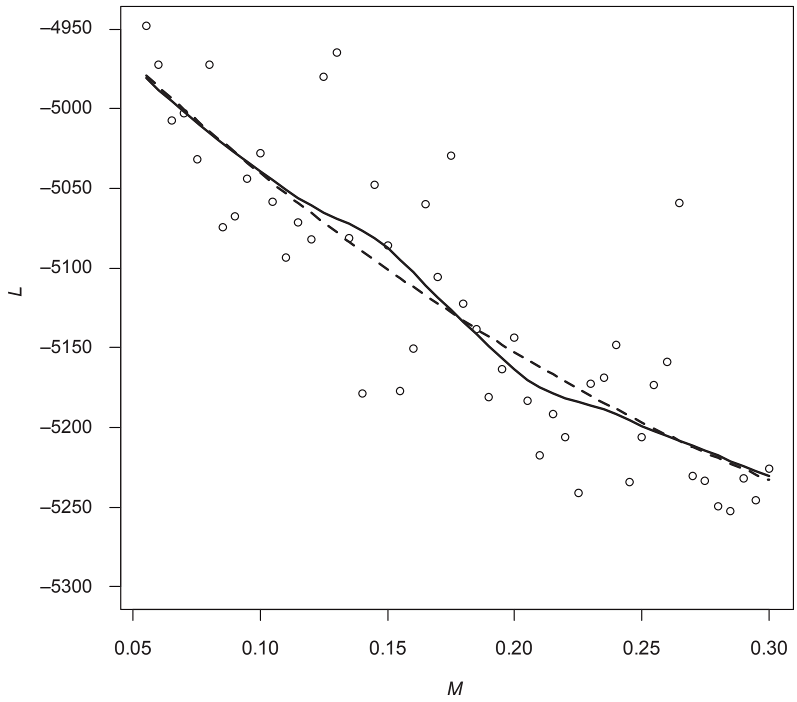


Figure 2: The –2 log-likelihood value (L) for the profile values of natural mortality (M) and the loess smoothed curve (solid line) (R-function `loess`) and quadratic regression (dashed line) fitted to the values of L for HIMI f2 data from fit of the BODE model.

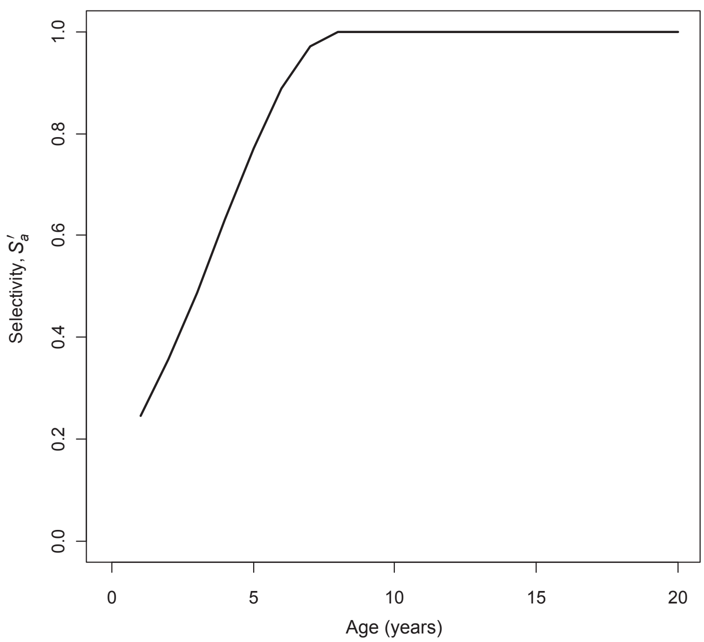


Figure 3: The BODE model fitted selectivity function, S'_a, for the estimated MLE for M of 0.209.

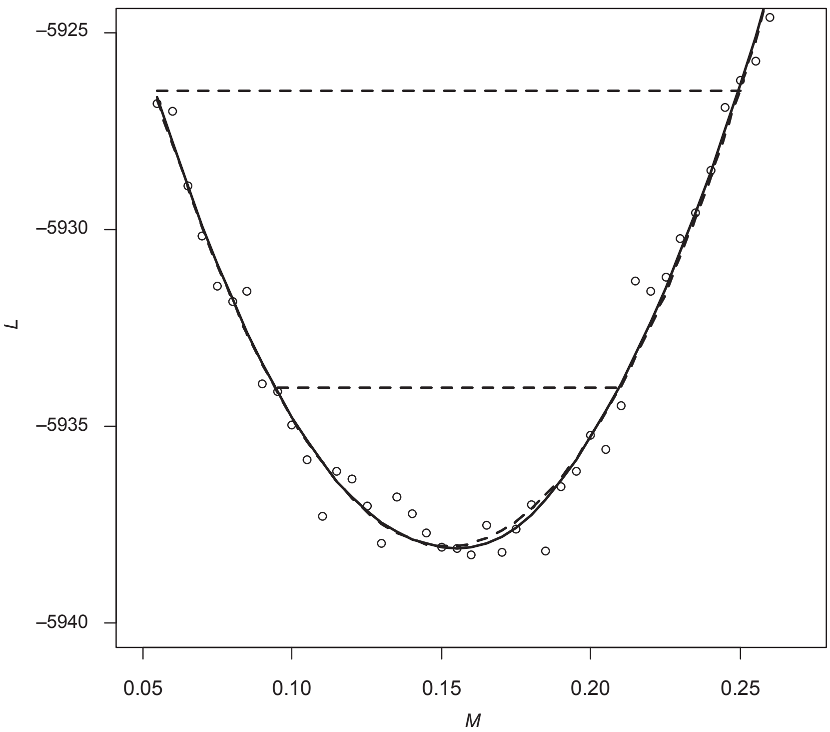


Figure 4: The –2 log-likelihood value (L) for the profile values of natural mortality (M) and the loess smoothed curve (solid line) (R-function `loess`) and quadratic regression (dashed line) fitted to the values of L for HIMI f2 data from fit of the CCODE model. The upper horizontal dashed line delineates the approximate 95% confidence limit of the minimum profile estimate using the estimate of ϕ of 3, while the lower horizontal dashed line delineates the approximate 95% confidence limit of the minimum profile estimate using a value of ϕ of 1.

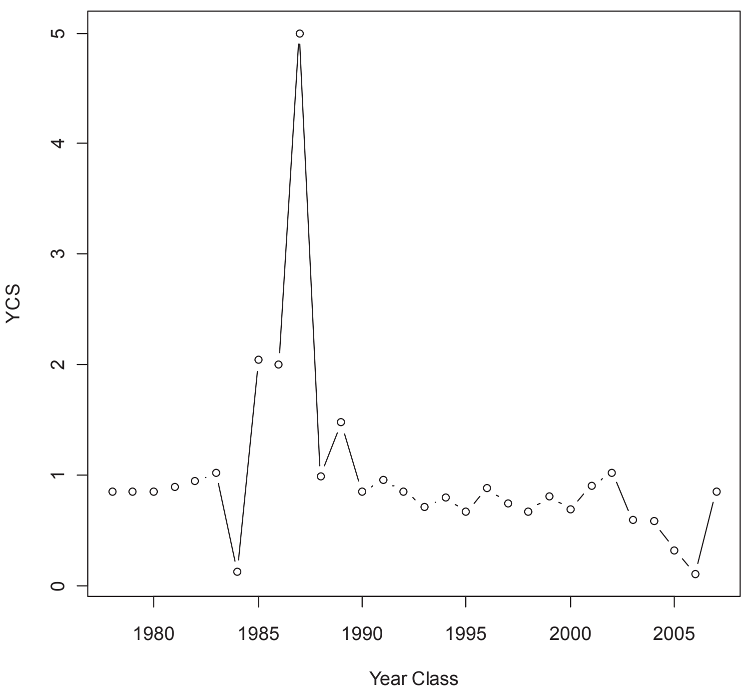


Figure 5: Estimated YCS parameters for the CCODE model for PMLE of M of 0.155.

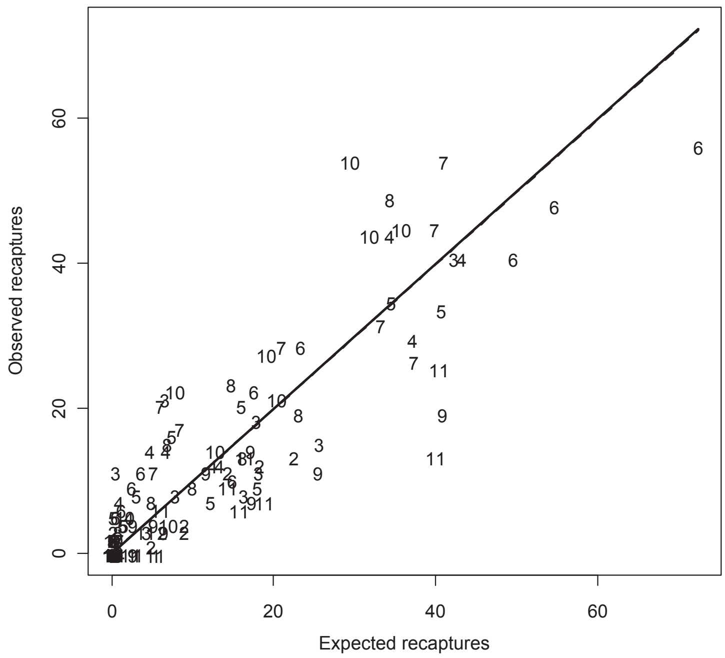


Figure 6: Observed and expected (i.e. estimated) number of recaptures across years and age classes, showing the 1:1 (solid) line and the best-fitting Poisson GLM regression line (dashed) through the origin for the CCODE model with expected number obtained for PMLE of *M* of 0.155. The labels represent the year number of recapture (1 = 1998,…,11 = 2008).

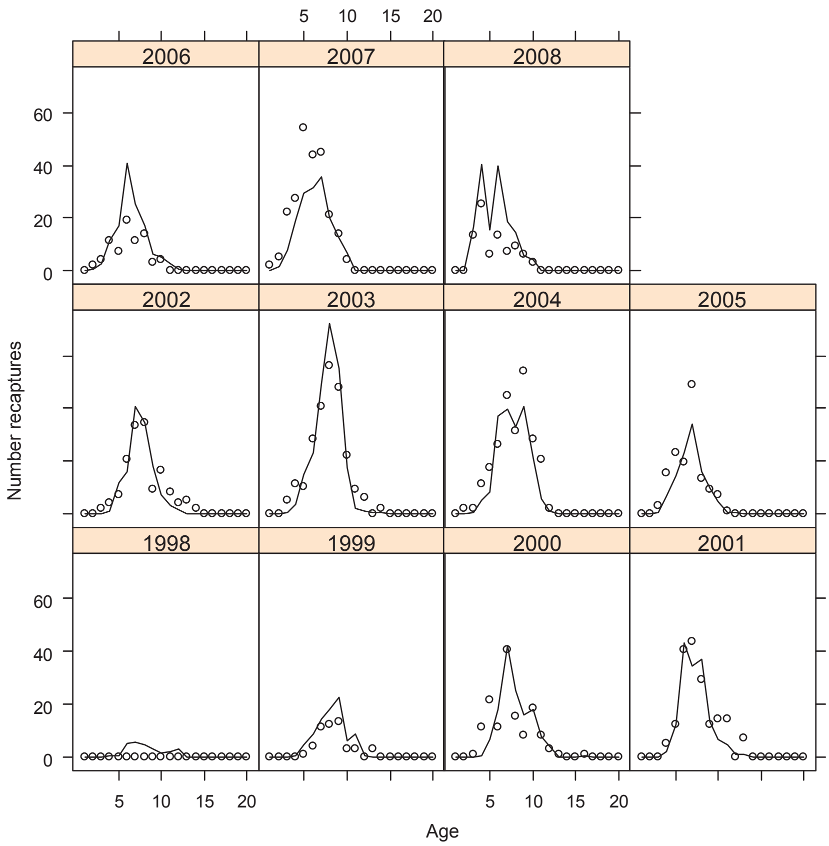


Figure 7: Observed (points) and expected (i.e. estimated) (lines) number of recaptures versus age for each fishing year for the CCODE model with expected number obtained for PMLE of *M* of 0.155.

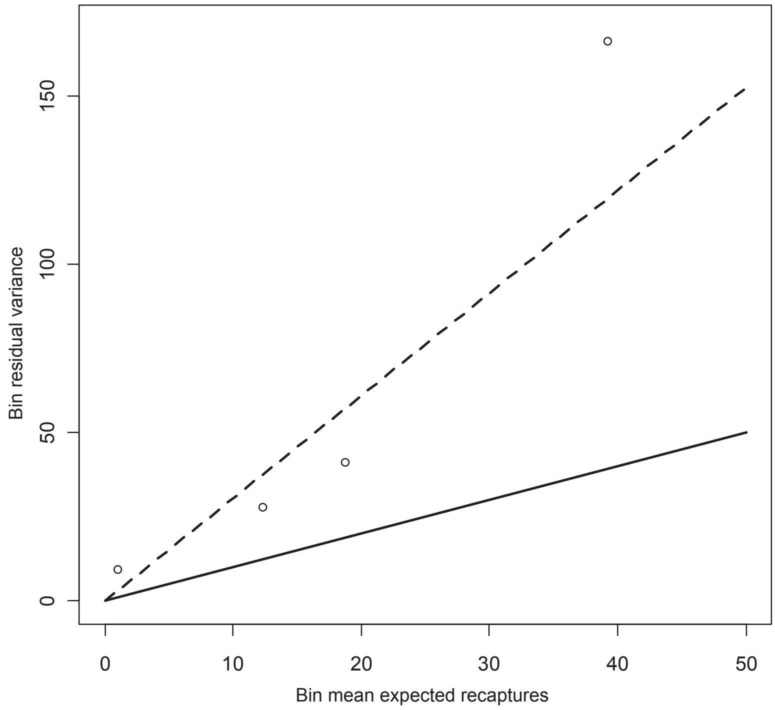


Figure 8: Estimated linear regression (dashed line) between residual variance and mean expected number of recaptures for binned values (points) showing 1:1 line (solid line). Expected number obtained for PMLE of *M* of 0.155. The 1:1 line represents Poisson variation, the regression line, with slope of ϕ = 3.05 indicates over-dispersion relative to a Poisson.

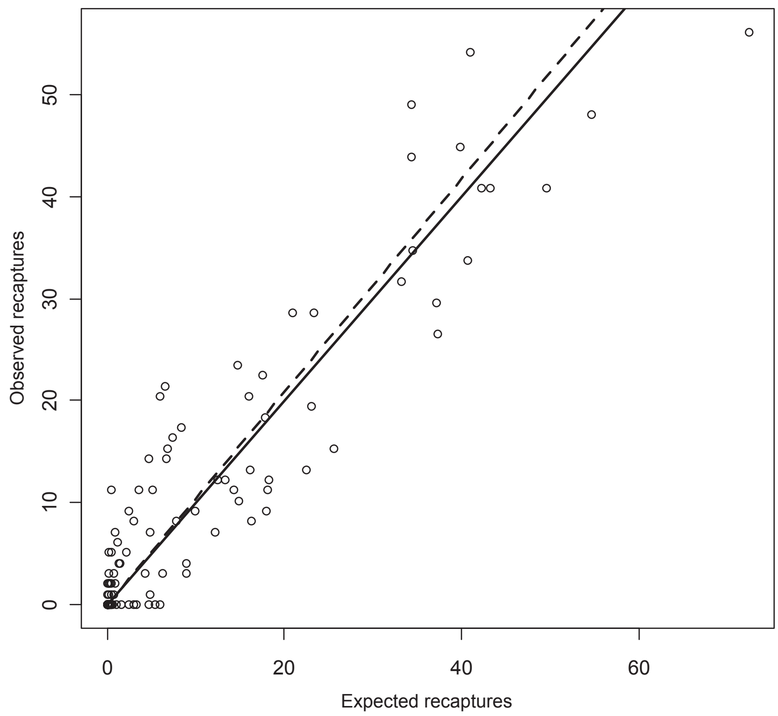


Figure 9: Observed and expected (i.e. estimated) number of recaptures across years and age classes for years up to, and including, 2005, showing the 1:1 (solid) line and the best-fitting Poisson GLM regression line (dashed) through the origin for the CCODE model with expected number obtained for PMLE of *M* of 0.155.

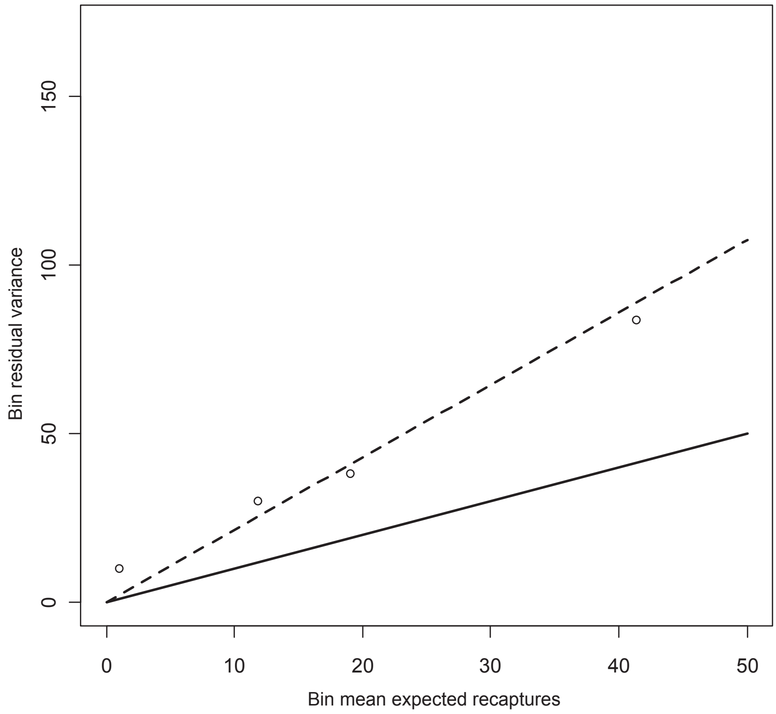


Figure 10: Estimated linear regression (dashed line) between residual variance and mean expected number of recaptures for binned values (points) showing 1:1 line (solid line) for years up to, and including, 2005. Expected number obtained for PMLE of *M* of 0.155. The 1:1 line represents Poisson variation, the regression line, with slope of $\phi = 2.15$ indicates over-dispersion relative to a Poisson.