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Stock assessment incorporating discards estimates in some years and implications for prediction of future stock trajectories

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Abstract

A Bayesian age-structured stock assessment model is developed that takes into account the information available about discards and is able to handle gaps in the time series of discards estimates. The model incorporates a term reflecting mortality due to discarding and appropriate assumptions about how this mortality may change over time are made. The result is a stock assessment that takes due account of the available information on discards while, at the same time, producing a complete time series of discards estimates. The method is applied to the hake stock in ICES divisions VIIIc and IXa, which experiences very high discarding on the younger ages. The stock is fished by Spain and Portugal and for each country there are only discards estimates for recent years. Furthermore, the years for which Portuguese estimates are available are only a subset of the years with Spanish estimates. Two runs of the model are performed, one assuming zero discards and another one incorporating discards. Assessment results and projections of future stock trajectories are compared and discussed and implications for management commented on.

Keywords: Bayesian, discards, hake, Markov chain Monte Carlo, population dynamics, stock management

1. Introduction

Discarding, referring to the practice of returning caught fish to sea, is a serious problem in many fisheries worldwide. Discarding practices can be due to different reasons, for example, not being legal to land the fish (if it is below some established minimum landing size or the allocated fishing quota has been reached) or to the fish having low market value (see e.g. Catchpole et al., 2005). They may also be driven by occurrence of high year classes, resources availability or environmental conditions (Rochet and Trenkel, 2005). Discarding is particularly harmful for the sustainability of biological populations, as it tends to concentrate mostly on young fish, which are killed before they have had a chance to reproduce. Regulatory efforts are constantly being made in order to try and minimise discarding practices, with the European Commission being actively involved in that effort.

A recognised problem in many stock assessments is that they do not take discards into account and implicitly assume no discarding, which can be very far from the truth (Pitcher *et al.*, 2002). Whereas many assessments use landings data going back a few decades, most countries have only started discards sampling programmes in recent years. The fact that time series of discards estimates are incomplete hampers seriously their incorporation in stock assessments.

In this paper a Bayesian age-structured assessment model is developed that is able to incorporate coherently discards estimates when they are available in just some years. The mechanism for achieving this is explicitly to incorporate a term in the model to account for fishing mortality due to discarding and to make appropriate assumptions about how it may change over time, hence getting around the problem of gaps in the time series of discards estimates. The approach can also handle other deficiencies in the discards data, for example, the situation where estimates of discards are available for only some of the fleets that take part in a particular fishery, or when there are estimates of discards for different fleets in non-coincident years. The key is again to make appropriate assumptions about mortality due to discarding corresponding to the missing fleets and/or years. The main products of this work are more realistic stock assessments, providing better estimates of abundance and fishing mortality, and improved prediction ability. As a by-product, complete time series of discards estimates are also obtained.

The model developed here falls within the general class of statistical catch-at-age models (Deriso *et al.*, 1985; Fournier and Archibald, 1982; Fryer, 2002), which acknowledge that there is uncertainty in the catch data and incorporate this in the model by means of, so-called, observation equations. The idea of separating the landed and (possibly various) discarded components of the catch, assigning a separate observation equation to each component, was already suggested by Punt *et al.* (2006) and the ideas developed here are within their general approach. Other recent work in this direction is in Aarts and Poos (2009).

In a Bayesian context, prior distributions must be assigned to all unknown model parameters. These distributions are meant to reflect expert knowledge had about model parameters before examining the current set of data. Such knowledge would normally come from scientific studies about the species (or about other closely related species) biology, behaviour, etc, as well as reflect fishing practices. When such expert knowledge is not available, a common approach is to choose fairly "non-informative" (loosely speaking, difuse) prior distributions, with the intention of preventing them from having strong influence on the results of the analysis. Since the development of powerful computational algorithms during the 1990's, the Bayesian approach has gained considerable increased use in fisheries (see e.g. McAllister and Ianelli, 1997; Punt and Hilborn, 1997; Meyer and Millar, 1999a, b; Millar and Meyer, 2000 a,b; Mäntyniemi and Romakkaniemi, 2002; Hvingel and Kingsley, 2006; Michielsens *et al.*, 2006; Newman *et al.*, 2006 and Ibaibarriaga *et al.*, 2008). The Bayesian method provides a coherent framework for uncertainty treatment, with the uncertainty present in the prior distribution being updated into posterior uncertainty (by taking into consideration the information coming from the observed data), which is, in turn, automatically propagated into any future predictions.

Motivation for this work arose from the assessment of the hake (*Merluccius merluccius*) stock in ICES divisions VIIIc and IXa, but the main ideas presented in this paper should be applicable to many other stocks. The hake stock is exploited by Spain and Portugal and has been assessed by ICES using a Bayesian statistical catch-at-age model with two fishing mortality separability periods (ICES, 2008a). Landings data start in year 1982. There are estimates of Spanish discards starting from 1994, with many gaps in the series, and of Portuguese discards since 2004. As a consequence of the many gaps in the time series of estimates, discards were not incorporated in the ICES assessment, which assumed zero discards. However, estimates for the available years indicate that discards on younger ages are very substantial, raising concern about the possible consequences of ignoring this important source of mortality in the assessment.

The Bayesian assessment model proposed here is next presented in detail, paying particular attention to the aspects related to the inclusion of incomplete discards information. This will be followed by the application to the hake stock, focussing the discussion mainly on the comparison of assessment and projection results between the cases where discards information is included in or excluded from the assessment. A final section will present conclusions and indicate directions of future work.

2. Assessment model

Throughout, $N(y,a)$ will denote the number of individuals of age a at the beginning of year y. For the general description of the model, the years will be labelled as $y = 1,...,Y$ and the ages as $a = 0,..., A+$, where A-1 is the last true age and A+ a plus group consisting of individuals aged A or older. Details of the model and prior distributions are described in the sequel.

2.1. Population dynamics model and prior distributions

Population dynamics are assumed to be governed by the usual equations for closed populations:

(1) $$N(y,a) = N(y-1,a-1)\exp[-Z(y-1,a-1)] \ , \ \text{if} \ 1 \le a \le A-1,$$

(2) $$N(y,A+) = N(y-1,A-1)\exp[-Z(y-1,A-1)] + N(y-1,A+)\exp[-Z(y-1,A+)],$$

where $F(y,a)$ is the fishing mortality rate and $Z(y,a) = F(y,a) + M$ the total mortality rate. The natural mortality rate M is assumed to be known and the same for all ages and years.

Yearly recruitments (age 0 individuals) and numbers-at-age in the initial year are unknown model parameters. As they must be non-negative, Log-Normal are reasonable choices of prior distributions. For yearly recruitments, independent prior distributions are assumed:

(3) $$N(y,0) \sim LogN(median = \mu_R, CV = \psi_R),$$

with μ_R and ψ_R to be chosen by the analyst. Similarly, numbers-at-age in the initial year are assigned independent distributions for the different ages:

(4) $$N(1,a) \sim LogN(median = \mu_1(a), CV = \psi_1),$$

with appropriate values of $\mu_1(a)$ and ψ_1 again to be chosen by the analyst.

2.2. Modelling $F(y,a)$ taking account of discards

The fishing mortality rate will be decomposed into terms corresponding to landings and discards. For ease of presentation, it will be assumed throughout the paper that there are two fleets fishing the stock, but the extension to more fleets is immediate. A common situation is that stock landed numbers-at-age are known for every year, whereas estimates of numbers-at-age discarded by the fleets are available only for some, not necessarily coincident, years. It then seems natural to decompose the total fishing mortality rate as

(5) $$F(y,a) = F_L(y,a) + F_{D,1}(y,a) + F_{D,2}(y,a),$$

where $F_L(y,a)$, $F_{D,1}(y,a)$ and $F_{D,2}(y,a)$ relate to the total stock landings, and discards from each of the two fleets, respectively. A main point here is that $F(y,a)$ is decomposed into disjoint terms adding up to the total fishing mortality rate for the stock.

When there are gaps in the time series of discards estimates, it is not possible to estimate the full matrices of $F_{D,1}(y,a)$ and $F_{D,2}(y,a)$ values, and their dimensions must be reduced by making judicious assumptions about the stock and fishery. The separability-type approach that was applied to the hake stock is next described. It is presented in this general section because the same or a suitably modified approach is likely to be applicable to many other stocks.

For the hake stock three time periods were considered, with selectivities-at-age assumed to be constant over time during the first and third periods and autoregressive in time during the intermediate period. This choice was made because the hake fishery is thought to have been rather stable during the first and third periods, whereas it underwent several progressive changes (enforcement of the minimum landing size, reduction of the long-line fleet and a change of mesh size) during the intermediate period. To translate these ideas into a modelling framework, first define

$$(6) \quad F_L(y,a) = f(y)r_L(y,a),\ F_{D,1}(y,a) = f(y)r_{D,1}(y,a),\ F_{D,2}(y,a) = f(y)r_{D,2}(y,a),$$

where $f(y)$ is a common factor related to yearly fishing effort. Now consider the three time periods bracketed by the years $1 < Y_1 < Y_2 < Y$. Details of how $r_L(y,a)$ was modelled follow:

For the intermediate period $y = Y_1,\ldots,Y_2$, a Normal AR(1) model for $\log\left(r_L(y,a)\right)$ was assumed, with autocorrelation parameter ρ_L and stationary distribution corresponding to

$$(7) \qquad r_L(y,a) \sim LogN\left(median = \mu_{r,L}(a), CV = \psi_{r,L}(a)\right).$$

A Uniform(0,1) prior distribution was assigned to the parameter ρ_L. During the first and third periods, selectivities-at-age are constant in time, as follows:

(8) For $y < Y_1$: $r_L(y,a) = r_L(Y_1,a)$; For $y > Y_2$: $r_L(y,a) = r_L(Y_2,a)$.

The same modelling procedure was applied to $r_{D,1}(y,a)$ and $r_{D,2}(y,a)$ for the young ages susceptible of being discarded. For older, non-discarded ages, $r_{D,1}(y,a) = r_{D,2}(y,a) = 0$.

The yearly factor $f(y)$, common to the three components of the fishing mortality, will also be estimated. Multiplying $f(y)$ by any value and dividing the three selectivity terms by the same value leaves the equations in (6) invariant. To get around this lack of identifiability, the landings selectivity-at-age can be set to 1 for an arbitrarily chosen age. If the latter is an age for which there are no discards, then $f(y)$ is simply interpreted as the fishing mortality of that age. A Normal AR(1) model seems like a sensible prior distribution for $\log(f(y))$. Hence

(9) $$f(y) \sim LogN\left(median = \mu_f, CV = \psi_f\right)$$

and there is a time autocorrelation parameter ρ_f, to which a Uniform(0,1) prior distribution has been assigned. Suitable values of μ_f and ψ_f are to be chosen by the analyst.

2.3. Observation equations for commercial landings and discards data

So far the age-structured population dynamics model has been defined, including prior distributions on the parameters to be estimated. Now the information provided by the available data and how it relates to the underlying population abundances and model parameters must be considered. This will be done by defining so-called observation equations, which provide stochastic links between observed data and model abundances and parameters. Once again, prior distributions will be set on any unknown parameters intervening in the observation equations.

The commercial catch data consist of stock landed numbers-at-age in all years and numbers-at-age discarded by each of the two fleets for some, not necessarily coincident, years. Each of these sources of information will be assigned its own observation equations, with a separate equation for each age. For the landed numbers-at-age, these are as follows:

(10) $L(y,a) \sim LogN\left(median = N(y,a)\{1-\exp[-Z(y,a)]\}F_L(y,a)/Z(y,a), CV = \psi_L(a)\right)$,

whereas for the discards from the each of the two fleets the equations are exactly the same replacing "L" by "D ,1" and "D,2", respectively, everywhere in expression (10).

The median of the Log-Normal distribution in (10) is obtained by applying Baranov catch equation to the model population abundances using the appropriate term, $F_L(y,a)$, of the fishing mortality rate. Discards of each of the fleets will also be related to population abundances via Baranov catch equation using $F_{D,1}(y,a)$ and $F_{D,2}(y,a)$, respectively.

The CVs of the Log-Normal observation equations are treated as unknown parameters. For computational simplicity, it is customary to set Gamma prior distributions on the precisions (inverse of variances) of Normal distributions. The variance of the Normal observation equation corresponding to (10) when considering the logarithm of the landed numbers-at-age is $\log[1+\psi_L(a)^2]$, so applying this procedure results in the prior distribution

(11) $$1/\log[1+\psi_L(a)^2] \sim Gamma\left(shape = u_{\psi,L}, rate = v_{\psi,L}\right),$$

assumed to be independent over the ages. To treat discards from the fleets in a similar way, it is enough to replace the subscript "L" by "D,1" or "D,2" in (11), as appropriate. The parameters of the Gamma prior distribution can be chosen on the basis of the implied distribution for $\psi_L(a)$, while remembering that $\psi_L(a)$ is the CV of the observation equation for landed numbers-at-age. For example, taking $u_{\psi,L} = 4$ and $v_{\psi,L} = 0.345$, the prior distribution of $\psi_L(a)$ has median 0.31 and (0.20, 0.61) as 95% central probability interval.

2.4. Observation equations for relative indices of stock abundance

Another important source of information in stock assessments comes from time series of relative indices of abundance-at-age (often referred to as "tuning series"). These may be obtained from research surveys or correspond to cpues of commercial fleets.

Let $I_i(y,a)$ be a relative abundance index corresponding to tuning fleet "i", which operates during the fraction of the year $[\alpha_i,\beta_i]\subseteq[0,1]$. For each year and age for which the index is available, the following observation equation is considered

(12)

$$I_i(y,a)\sim LogN\left(median = q_i(a)N(y,a)\frac{\exp[-\alpha_i Z(y,a)]-\exp[-\beta_i Z(y,a)]}{(\beta_i-\alpha_i)Z(y,a)}, CV=\psi_i(a)\right)$$

The median of the Log-Normal distribution is the average stock abundance during the period in which the tuning fleet operates, multiplied by the age and fleet specific catchability $q_i(a)$. This catchability is assumed constant over time, but unknown, with Log-Normal prior distribution:

$$q_i(a)\sim LogN\left(median=\mu_{q,i}, CV=\psi_{q,i}\right). \tag{13}$$

It is often assumed that catchability remains constant above a certain age (so-called "q-plateau").

The prior distribution of the CV of the observation equation will be set according to the procedure followed for the CV of the observation equations for landings and discards. Hence:

$$1/\log[1+\psi_i(a)^2]\sim Gamma\left(shape=u_{\psi,i}, rate=v_{\psi,i}\right) \tag{14}$$

where, again, the shape and rate parameters of the Gamma prior distribution can be chosen on the basis of the implied prior values for $\psi_i(a)$.

A similar procedure is repeated for each of the tuning fleets.

3. Application to the stock of hake in ICES divisions VIIIc and IXa

3.1. Data, priors and computational method

For the stock of hake in ICES divisions VIIIc and IXa, the available data consist of stock landed numbers-at-age for years y = 1982,..., 2007 and ages a = 0,...,8+; estimates of numbers discarded by Spain (fleet "$D,1$" in the notation used for the general model description) for years 1994, 1997, 1999, 2000, 2003-2007 and ages 0-3; estimates of numbers discarded by Portugal (fleet "D,2") for years 2004-2007 and ages 0-3; it is assumed that there is no discarding above the age of 3. These discards refer to the trawling fleet, which discards big amounts of small fish. Discards in other fleets, such as gillnetters and longliners, are not considered here since their catches are virtually always above the minimum landing size (27 cm).

Two research surveys (Spanish and Portuguese) and three cpue series arising from the commercial trawl fleets of A Coruña and Portugal provide relative indices of abundance-at-age, with the surveys covering ages 0-4 and commercial cpues ages 4-8+.

The assessment performed by ICES in 2008 for this stock used all the information indicated above with the exception of the discards estimates, assuming that there was no discarding. Details of that assessment, including the data, can be found in ICES (2008a). The only data presented in this paper are the discarded numbers-at-age (Tables 1 and 2), as these were not included in the ICES document.

As indicated in the general model description, the model applied to the hake stock considers three separability-type periods for the selectivities-at-age, which correspond to years 1982-1990 and 2001-2007 (constant in time selectivities) and 1990-2001 (autoregressive in time selectivities). The ICES 2008 assessment model used a simpler specification, with two time periods of separability and no autoregressive part. The somewhat more complex formulation in the present paper was introduced because it is more in accordance with knowledge had about the hake fishery, as it has already been indicated. Natural mortality was taken to be $M = 0.2$.

The prior distributions were centred at values deemed reasonable according to the current knowledge about this stock and the fishery, while, at the same time, they were assigned large CVs, so as to prevent them from having an unduly high influence on posterior results. The most difficult aspect was to choose the prior medians of the selectivities of landings, Spanish and Portuguese discards ($\mu_{r,L}(a)$ in equation 7 and, similarly, $\mu_{r,D,1}(a)$ and $\mu_{r,D,2}(a)$), as the only information available came from the discards estimates themselves. These medians were finally taken equal to the proportion of individuals estimated to have been landed, discarded by Spain and discarded by Portugal, respectively, averaged over the years for which there are estimates of the three quantities (2004-2007) and subsequently divided by two for ages 0 and 1 (to reflect a notion of lower fishing mortality for those ages). This (slight) use of data information was made in order to avoid having prior distributions that were in contradiction with the observed data (other choices tried generally gave bad residuals for age 0 landings, although minor model modifications, such as using time-varying instead of constant values for these medians were subsequently seen to improve the residual pattern). Table 3 displays all the prior choices made and gives the prior 95% probability intervals for the corresponding parameters. The intervals are generally very wide, as was intended.

As is usual in Bayesian inference, model fitting was done using the computational method known as Markov chain Monte Carlo (MCMC) to simulate the posterior distribution (see Gilks *et al.*, 1996, for an accesible introduction to MCMC). This was programmed in the free software WinBUGS (Lunn *et al.*, 2000), downloadable from http://www.mrc-bsu.cam.ac.uk/bugs, and run from R using the R2WinBUGS package, which is also free software available at http://cran.r-project.org. MCMC simulates random draws from the posterior distribution in a dependent fashion, with each draw depending on the one immediately preceding it. As a consequence, many iterations are typically needed to obtain a representative sample from the posterior distribution, particularly when it is highly dimensional and strong correlations between some of its dimensions exist. Usually, an initial number of draws is discarded ("burn-in") to mitigate the effect of start up values, after which only one every several draws is recorded ("thinning") in order to reduce autocorrelation in the kept sample. The results presented in this paper are based on a chain with a burn-in period of 32 000 iterations, followed by 80 000 additional iterations. Of the latter, one every 16 iterations was kept, leading to a sample of 5000 draws which, after suitable examination and convergence checks, was considered to be a good representation of the posterior distribution. Running time was approximately 32 hours on a standard desktop PC. Although much shorter runs led to similar results, these very long runs were conducted in order to get valid estimates of 95% posterior probability intervals.

3.2. Assessment results

To assess the effect that the assumption of zero discards has on the hake assessment, two runs have been performed: a main one that incorporates the available discards estimates and a second one that assumes zero discards. Exactly the same priors were used in both runs, except for the fact that $r_{D,1}(y,a) = r_{D,2}(y,a) = 0$ in the run assuming zero discards.

Figure 1 presents posterior estimates (median and 95% probability intervals) of stock strends for SSB (tonnes), recruitment (thousands of age 0 individuals) and Fbar (average fishing mortality over ages 2-5). Solid and open circles correspond to the runs including and excluding discards, respectively. Whereas including discards information in the assessment has negligible impact on inference on SSB, its effect on recruitment estimates is very pronounced, with 95% probability intervals that typically do not overlap with those obtained under the assumption of zero discards. The 95% posterior probability intervals for recruitment are considerably wider for the run that includes discards, reflecting the fact that discards information is missing in many years. Fbar is estimated to be somewhat higher in the run that includes discards.

Figure 2 displays the posterior densities of the relative exploitation pattern-at-age (F-at-age divided by Fbar) applicable to the whole period 2001-2007, with solid and dashed lines corresponding to the assessments with and without discards, respectively. As expected, taking discards into account shifts the estimated relative exploitation pattern towards younger ages, with the biggest changes occurring for age 0 and 1 individuals.

Accounting for discards also permits the estimation of the fishing mortality rates corresponding to discarding ($F_D(y,a) = F_{D,1}(y,a) + F_{D,2}(y,a)$, see equation 5), presented in Figure 3 as posterior medians and 95% probability intervals. Discarding mortality is estimated to be substantial for ages 0-2 (roughly of the order of 0.2) and much lower for age 3 (around 0.02). The sparsity of the discards information is again reflected in the wide posterior probability intervals. Figure 4 displays posterior estimates of $F_D(y,a)/F(y,a)$, which is the probability that a fish is discarded given that it has been caught, for the different years and ages. From the model definition, these probabilities are constant over the periods 1982-1990 and 2001-2007. Despite the big uncertainty associated with many of these estimates, it is clear that this probability has increased over time for ages 0 and 1. This is in agreement with a progressive enforcement of the minimum landing size for this stock. As a by-product of the analysis, discarded numbers-at-age can be estimated for the stock in all years, by calculating the posterior distribution of $N(y,a)\{1-\exp[-Z(y,a)]\}F_D(y,a)/Z(y,a)$. Results are displayed in Figure 5. Again, the sparsity of discards information induces great uncertainty in the estimates. Nonetheless, the estimated values will the most coherent with the various sources of information that were incorporated in the model.

There are residuals for stock landed numbers-at-age every year, Spanish and Portuguese discarded numbers-at-age for the years for which there are data, as well as residuals for the five abundance-at-age tuning index series used. Residual plots are not presented here due to space considerations, but their examination did not reveal any striking or particularly worrying patterns. Landings residuals are of larger magnitude for age 0 than for older ages. This could be due to the fact that age 0 landings have decreased very substantially over time and have been extremely low for approximately one decade, hence becoming difficult to sample. Spanish and Portuguese discards residuals are difficult to interpret, since they correspond to very few years. On the whole, they look reasonable, although more years would be necessary to study possible patterns. Tuning series residuals also look reasonable, being quite similar to those in the currently approved ICES assessment (ICES, 2008a).

Plots comparing prior and posterior distributions (not presented either) were also examined for all parameters. They generally show posterior distributions that are much more concentrated than the priors and often centred at different values, indicating that the data are informative about many model parameters. However, some sensitivity of recruitment estimates to the prior median values chosen for the yearly recruitments has been detected. Additionally, results on selectivity-at-age of discards (and, consequently, the probability of discarding fish once caught, discarded numbers and recruitment) for the years before any discard data are available have been found to be very sensitive to the prior distribution chosen for the discards selectivity-at-age parameters in the early time period. This is not surprising: given the lack of discard data in those years, such estimates must rely on landings data and abundance-at-age indices, assumed to have constant catchability over time. However, both landings and available abundance indices for hake are very noisy for age 0 and the data signal is not strong enough to reconstruct discards just from the data, giving rise to strong sensitivity to the prior choice. All this must be kept in mind when examining stock-recruitment plots and interpreting the results of future stock projections. In practice, a prior sensitivity study must always be conducted before using results to give management advice. The authors are currently examining this issue in detail (particularly, as the discards estimates presently obtained for the earlier period seem too high given that the minimum landing size was only implemented from 1991; therefore, a prior distribution implying very low discards before 1991 is likely to be more realistic than the one used so far) and will report on it in a later version of this paper. Results from the present version of this paper must, thus, be considered as preliminary.

Figure 6 is a stock-recruitment plot based on posterior medians of SSB and recruitment. Solid and open circles correspond to the runs accounting for and excluding discards, respectively. Clearly, the perception of the stock-recruitment relationship changes depending on whether discards are or are not accounted for in the assessment. The change in the stock-recruitment relationship could have an impact when calculating biological reference points and other target or limit points used for stock management (see e.g. Brodziak and Legault, 2005). Figure 6 also marks with vertical dashed lines the values of $B_{\mathrm{lim}} = 25000$ tonnes and $B_{\mathrm{pa}} = 35000$ tonnes currently used for this stock.

3.3. Projections

Assessment results have shown that the main impact of accounting for discards in the assessment is that higher estimates of recruitment and fishing mortality for the younger ages are obtained. Whereas this may seem of relatively minor importance given that SSB and Fbar estimates were not significantly altered, it can have a significant impact when making projections of future stock trajectories under different management scenarios, as will be shown in the sequel.

The starting point for projections is survivors-at-age at the end of the final assessment year (2007) or, equivalently, numbers-at-age at the beginning of the first projection year (2008). The latter are displayed in Figure 7, where the solid and dashed lines correspond to the assessments with and without considering discards, respectively. For ages 1 and older the figure displays posterior densities from the assessment model. No estimate of age 0 abundance in the first projection year is obtained from the assessment model. The age 0 panel of Figure 7 displays the recruitment distributions that will be used in all the projection years, which were obtained by randomly drawing from the posterior distributions of recruitments during 1989-2007 (excluding years before 1989 is the procedure currently followed by the ICES assessment working group for this stock). Clearly, the recruitment values used in the projections will be larger when discards are accounted for in the assessment.

From numbers-at-age at the beginning of 2008, the population will be projected forwards in time using the standard population dynamics equations (1) and (2), making assumptions about fishing mortality-at-age that are considered relevant from a stock management perspective.

Projections will take account of the uncertainty in the assessment results, particularly on the abundances-at-age at the beginning of 2008, recruitments and fishing mortalities-at-age on which the scenarios examined will be based. The correlations between all these quantities will also be accounted for. Since posterior distributions have been computed via simulation, incorporating the uncertainty and correlations in the projections is simply achieved by projecting forward from each of the posterior draws, using the same draw index for all the quantities (abundances, mortalities and recruitments) involved in the projection.

Projections will be presented for the period 2008-2016, as there is a recovery plan for the hake stock with the specific aim of achieving 35 000 tonnes of SSB by 2016. Weight-at-age and maturity-at-age used in the calculation of SSB will be taken to be the average of those quantities in the final three assessment years (2005-2007). Three projection scenarios will be considered, differing on the assumptions regarding F during the projection years:

Scenario 1: F-at-age equal to the average over the last three assesment years

Scenario 2: Starting from the values in the final assessment year, F-at-age decreases by 10% every projection year, with the same reduction applied to all ages, until this would result in Fbar falling below 0.27, at which point F-at-age is fixed with Fbar=0.27.

Scenario 3: Starting from the values in the final assessment year, F-at-age decreases every projection year by 30% for ages 0 and 1 and by 10% for older ages, until this would result in Fbar falling below 0.27, at which point F-at-age is fixed with Fbar=0.27.

Scenario 1 corresponds to F status-quo, Scenario 2 follows along the lines of the recovery plan (although these are simple projections and not an evaluation of the plan, which would be a far more complex exercise) and Scenario 3 is in the recovery plan spirit but applies a stronger reduction on the fishing mortality of ages 0 and 1, which are almost entirely discarded when caught (see Figure 4). Scenario 3 may thus reflect a situation where additional measures for discards reduction are applied. In all three scenarios, the probability that a fish is discarded when it is caught is assumed to remain constant during the projection years and equal to that of the period 2001-2007 (Figure 4).

Two questions of interest arise: on the one hand, how the different scenarios perform in terms of yield and recovery of SSB and, on the other hand, to what extent conclusions are affected by whether discards are included in the assessment or ignored. Figure 8 displays 12 panels, with upper, middle and lower rows corresponding to Scenarios 1, 2 and 3, respectively. Each column corresponds to a quantity of interest. From left to right these are Fbar, landings (tonnes), SSB (tonnes), and the probabilities that SSB is above the target of the recovery plan, 35 000 tonnes, and above $B_{\lim} = 25000$ tonnes. Each panel displays the results of the projections during years 2008-2016, in the form of medians (circles) and 95% probability intervals (segments). Solid and open circles correspond to the assessments with and without inclusion of discards, respectively.

The first row of Figure 8 clearly indicates that under F status-quo (Scenario 1), there will be no recovery of the stock, with SSB and landings both starting to decrease after some initial increase and with the probability of achieving 35 000, or even 25 000, tonnes of SSB being virtually 0 in 2016. Results are very similar regardless of whether discards are included in or excluded from the assessment. Scenario 2 (10% yearly reduction of F for all ages, halting the reduction once Fbar=0.27) shows much better stock recovery prospects, with the probability that SSB is above $B_{\lim} = 25000$ by 2016 reaching 0.99 and 0.90 for the models with and without discards, respectively. Under this scenario, more optimistic projections after a few years are obtained when discards are considered. This was to be expected given the similarity of results between including and excluding discards found in Scenario 1 and the reduction in F considered in Scenario 2. The percentage reduction in F has more impact when discards are included in the assessment as, in that case, F is estimated to be larger, particularly for the young ages. The combination of this and the larger recruitments estimated when discards are considered in the assessment (present in all three scenarios) leads to healthier stock sizes after a few years than the smaller recruitments estimated when discards are not considered in the assessment. This effect is amplified under Scenario 3, as in this case fishing mortality of ages 0 and 1 is assumed to be reduced more strongly. Under this scenario, the probability that SSB reaches at least 35 000 tonnes in 2016 is 0.97 when discards are considered in the assessment versus 0.26 when they are not.

4. Conclusions and directions for further work

This paper has developed a stock assessment model that can incorporate coherently incomplete information on discards. In particular, the model can handle gaps in the time series of discards estimates as well as missing discards estimates for some of the fleets fishing a particular stock. The model has been developed and fitted in a Bayesian context and applied to the hake stock in ICES divisions VIIIc and IXa, which provided the primary motivation for this work. Assessment results show that the main impacts of accounting for discards in the assessment are higher estimates of recruitment and fishing mortality for the younger ages, whereas the effect on estimates of SSB and Fbar is minor.

A projection exercise under different hypotheses about F showed that the inclusion or not of discards in the assessment can have substantial impact when predicting future stock trajectories. In this paper, recruitment values in the projection years were drawn randomly from those estimated for some of the assessment years. The larger recruitments estimated when discards were included in the assessment led to more optimistic future stock trajectories under F-reduction scenarios. The larger the reduction in F, particularly for the younger ages (the ones more susceptible of being discarded), the stronger the effect. Hence, disregarding discards when they are known to exist can give a misleading impression of future stock trajectories and accounting for discarding in the assessment process is an important step for improving management advice. However, as indicated in Section 3, results must be considered as preliminary until a sensitivity analysis is finalised. In particular, the strong sensitivity of the recruitment estimates in the earlier time period to prior assumptions can have an impact on projection results and this is currently being explored by the authors.

Although the main ideas of the assessment model presented here could be applied to many other stocks, some aspects will need modification before doing so. In particular, the three time periods considered when modelling the fishery selectivities-at-age for the hake stock will most likely require modifications for other stocks. When the model was tried on the North Sea haddock stock during the ICES working group on the Methods of Fish Stock Assessment (ICES, 2008 b), a unique time period was considered, with autoregressive-in-time selectivities throughout. It was then found that the fit to the discards (actually, bycatch in that instance) of a particular fleet was poor and the more likely explanation was thought to be that the assumption of a common factor $f(y)$ applying to all the fleets was not suitable because the fleets had markedly different effort patterns over time. In such cases, it may be appropriate to replace equations (5) and (6) by

$F(y,a) = f_1(y)[r_{L,1}(y,a) + r_{D,1}(y,a)] + f_2(y)[r_{L,2}(y,a) + r_{D,2}(y,a)]$, reflecting that each fleet has its own effort level giving rise to both its landings and discards. This more general model has not been fitted to any stock to date.

Another issue that merits further development is how the changed perception of the stock-recruitment relationship caused by the inclusion of discards impacts on biological reference points and other target and limit reference points used for stock management. Chen *et al.* (2007) found that ignoring discards may lead to overestimation of $F_{\max}$ and $F_{0.1}$. The authors are currently examining this for the hake stock and will also report on it on a later version of this paper.

Finally, having the discards fishing mortality of the various fleets included as part of the model (equation 5) gives a wider range of interesting scenarios than can be tried in projections. For example, the effect of strongly reducing specifically discards fishing mortality, either for all fleets combined or for particular fleets, could be examined. This would permit a more detailed evaluation of the likely impact of a wider range of management options and is another line of research that the authors plan to pursue.

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Table 1: Discarded numbers-at-age by Spain in the available years

Year	age 0	age 1	age 2	age 3
1994	8938.20	3961.20	170.10	186.80
1997	32180.50	13638.70	1028.80	41.40
1999	8013.30	4660.60	597.70	60.20
2000	3075.20	8377.60	2715.80	103.30
2003	1013.10	4963.20	751.40	17.40
2004	1074.10	2042.20	1107.10	0.05
2005	337.30	3050.40	959.10	123.10
2006	9006.60	20713.10	10840.90	192.70
2007	7086.70	8657.40	2878.30	59.70

Table 2: Discarded numbers-at-age by Portugal in the available years

Year	age 0	age 1	age 2	age 3
2004	7457.40	12089.10	1304.40	16.20
2005	5745.40	19904.00	3432.40	132.00
2006	5355.20	6837.90	2730.20	166.70
2007	11413.30	18672.80	4216.50	603.10

Table 3: Prior settings used in the hake stock analysis and corresponding 95% prior probability intervals

Parameter	Prior settings	95% probability interval
$N(y,0)$	$\mu_R = 80000\,, \psi_R = 2$	(6656,961557)
$N(1982,1)$	$\mu_1(1) = 48522\,, \psi_1 = 2$	(4037,583214)
$N(1982,2)$	$\mu_1(2) = 29430\,, \psi_1 = 2$	(2449,353737)
$N(1982,3)$	$\mu_1(3) = 14615\,, \psi_1 = 2$	(1216,175661)
$N(1982,4)$	$\mu_1(4) = 7257\,, \psi_1 = 2$	(604,87230)
$N(1982,5)$	$\mu_1(5) = 3604\,, \psi_1 = 2$	(300,43317)
$N(1982,6)$	$\mu_1(6) = 1790\,, \psi_1 = 2$	(149,21511)
$N(1982,7)$	$\mu_1(7) = 889\,, \psi_1 = 2$	(74,10682)
$N(1982,8+)$	$\mu_1(8+) = 877\,, \psi_1 = 2$	(73,10537)
$f(y)$	$\mu_f = 0.6, \psi_f = 1$	(0.12,3.07)
$r_L(y,0)$	$\mu_{r,L}(0) = 0.00015\,, \psi_{r,L}(0) = 5$	(4.4e-6,5.2e-3)
$r_L(y,1)$	$\mu_{r,L}(1) = 0.04\,, \psi_{r,L}(1) = 1$	(0.0078,0.2045)
$r_L(y,2)$	$\mu_{r,L}(2) = 0.61, \psi_{r,L}(2) = 1$	(0.1193,3.1190)
$r_L(y,3)$	$\mu_{r,L}(3) = 0.97,\ \psi_{r,L}(3) = 0.3$	(0.5456,1.7245)
$r_L(y,a), a = 4,5,7,8+$	$\mu_{r,L}(a) = 1,\ \psi_{r,L}(a) = 0.3$	(0.5625,1.7778)
$r_L(y,6) = 1$		
$r_{D,1}(y,0)$	$\mu_{r,D,1}(0) = 0.13305\,, \psi_{r,D,1}(0) = 1$	(0.0260,0.6803)
$r_{D,1}(y,1)$	$\mu_{r,D,1}(1) = 0.14\,, \psi_{r,D,1}(1) = 1$	(0.0274,0.7158)
$r_{D,1}(y,2)$	$\mu_{r,D,1}(2) = 0.18\,, \psi_{r,D,1}(2) = 1$	(0.0352,0.9204)
$r_{D,1}(y,3)$	$\mu_{r,D,1}(3) = 0.01\,, \psi_{r,D,1}(3) = 1$	(0.0020,0.0511)
$r_{D,2}(y,0)$	$\mu_{r,D,2}(0) = 0.3668\,, \psi_{r,D,2}(0) = 1$	(0.0717,1.8755)
$r_{D,2}(y,1)$	$\mu_{r,D,2}(1) = 0.32\,, \psi_{r,D,2}(1) = 1$	(0.0626,1.6362)
$r_{D,2}(y,2)$	$\mu_{r,D,2}(2) = 0.21\,, \psi_{r,D,2}(2) = 1$	(0.0411,1.0738)
$r_{D,2}(y,3)$	$\mu_{r,D,2}(3) = 0.02\,, \psi_{r,D,2}(3) = 1$	(0.0039,0.1023)
$\psi_L(a), \psi_{D,1}(a), \psi_{D,2}(a)$	$u_{\psi,L} = u_{\psi,D,1} = u_{\psi,D,2} = 4$ $v_{\psi,L} = v_{\psi,D,1} = v_{\psi,D,2} = 0.345$	(0.20,0.61)
$q_i(a)$, $a \le 6$,all fleets	$\mu_{q,i} = 0.0009\,, \psi_{q,i} = 12.14$	(1.1e-5,0.0730)
$q_i(a) = q_i(6)$, $a > 6$, all fleets		
$\psi_i(a)$,all fleets	$u_{\psi,i} = 4\,, v_{\psi,i} = 0.345$	(0.20,0.61)

List of figures

Figure 1: Estimated trends for the hake stock: SSB in tonnes (upper panel), Recruitment in thousands of individuals (middle panel) and Fbar from ages 2-5 (lower panel). Posterior medians (circles) and 95% probability intervals (segments). Open and close circles correspond to the assessments including and excluding discards, respectively.

Figure 2: Posterior distributions of relative exploitation pattern-at-age, $F(y,a)/Fbar(y)$, during 2001-2007. Each panel corresponds to one age. Solid and dashed lines correspond to the assessments including and excluding discards, respectively.

Figure 3: Estimated mortality at age caused by discarding (Spain and Portugal combined). Each panel corresponds to one age (ages 0-3). Posterior medians (circles) and 95% probability intervals (segments).

Figure 4: Estimated probability that an individual is discarded given that it has been caught, $F_D(y,a)/F(y,a)$. Each panel corresponds to one age (ages 0-3). Posterior medians (circles) and 95% probability intervals (segments).

Figure 5: Estimated discarded numbers-at-age for the whole of the stock (Spain and Portugal combined). Each panel corresponds to one age (ages 0-3). Posterior medians (circles) and 95% probability intervals (segments).

Figure 6: Stock-recruitment plot based on posterior medians. Solid and open circles correspond to the assessments including and excluding discards, respectively. $B_{\mathrm{lim}} = 25000$ tonnes and $B_{\mathrm{pa}} = 35000$ tonnes are indicated by vertical dashed lines.

Figure 7: Abundance-at-age at the beginning of the first projection year, with one panel for each age. For ages 1 and older, these are posterior distributions from the assessment model. For age 0, this corresponds to random drawing from the posterior distributions of recruitment for the period 1989-2007 as obtained from the assessment model. Solid and dashed lines correspond to the assessments including and excluding discards, respectively.

Figure 8: Projection results. From top to bottom, rows correspond to Scenarios 1 (F status-quo), 2 (10% yearly reduction in F) and 3 (30% and 10% yearly reductions in F for ages 0-1 and older than 1, respectively). From left to right, the four columns correspond to Fbar, landings (tonnes), SSB (tonnes) and $P(SSB > 25000)$ and $P(SSB > 35000)$. Projection medians (circles) and 95% probability intervals (segments). Solid and open circles correspond to the assessment models including and excluding discards, respectively.

Fig. 1

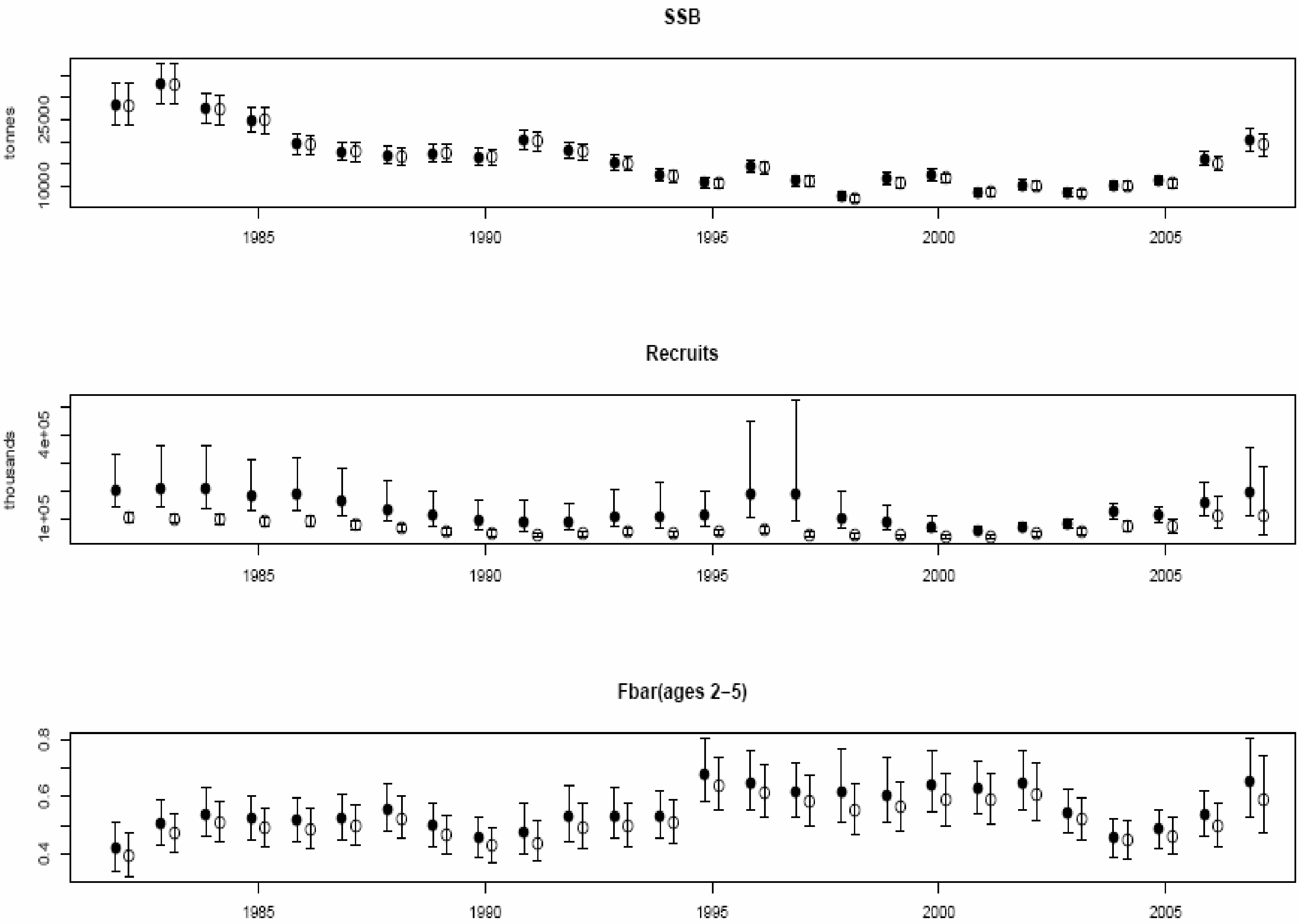

SSB
tonnes
10000
25000
1985
1990
1995
2000
2005
Recruits
thousands
1e+05
4e+05
1985
1990
1995
2000
2005
Fbar(ages 2–5)
0.4
0.6
0.8
1985
1990
1995
2000
2005

Fig. 2

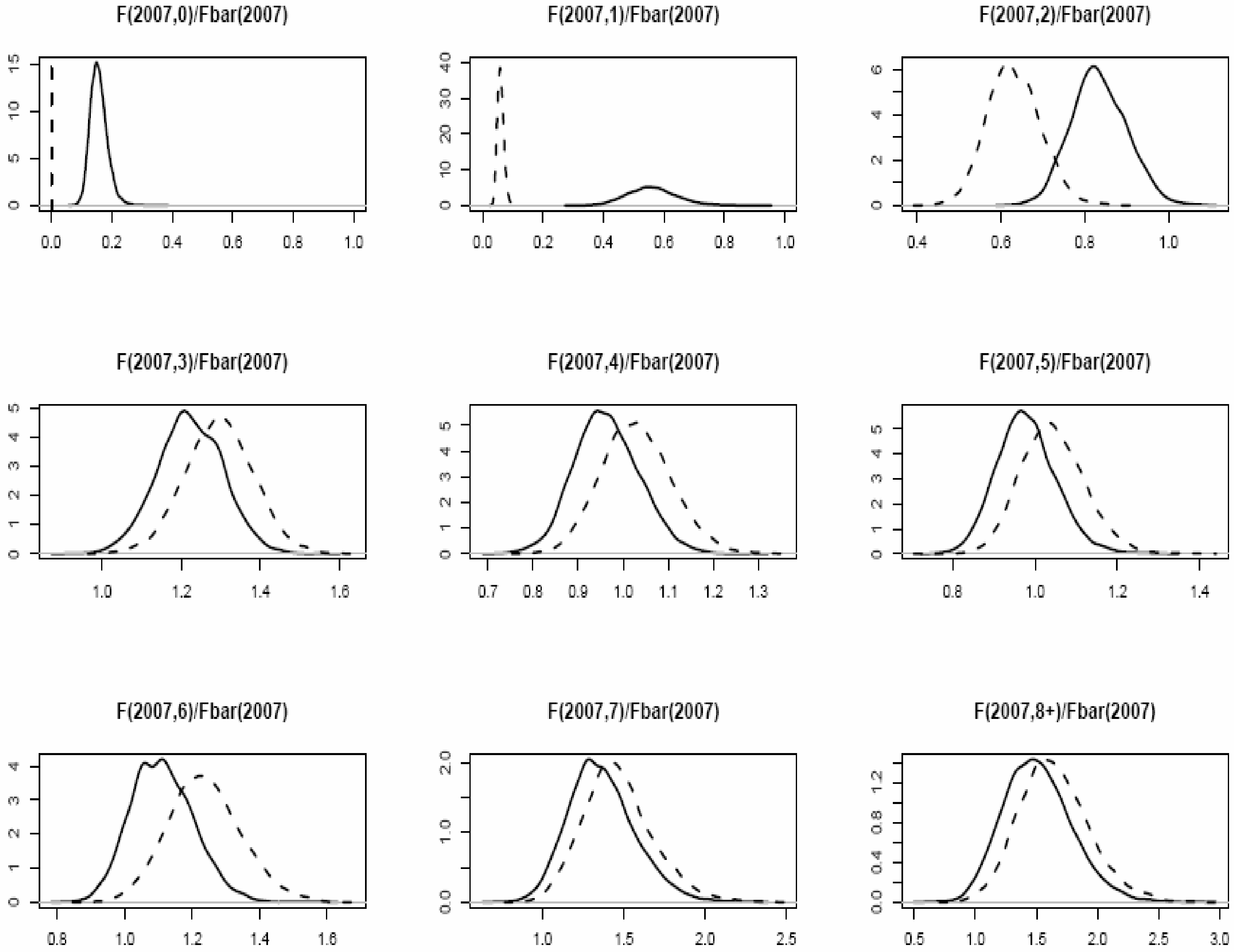
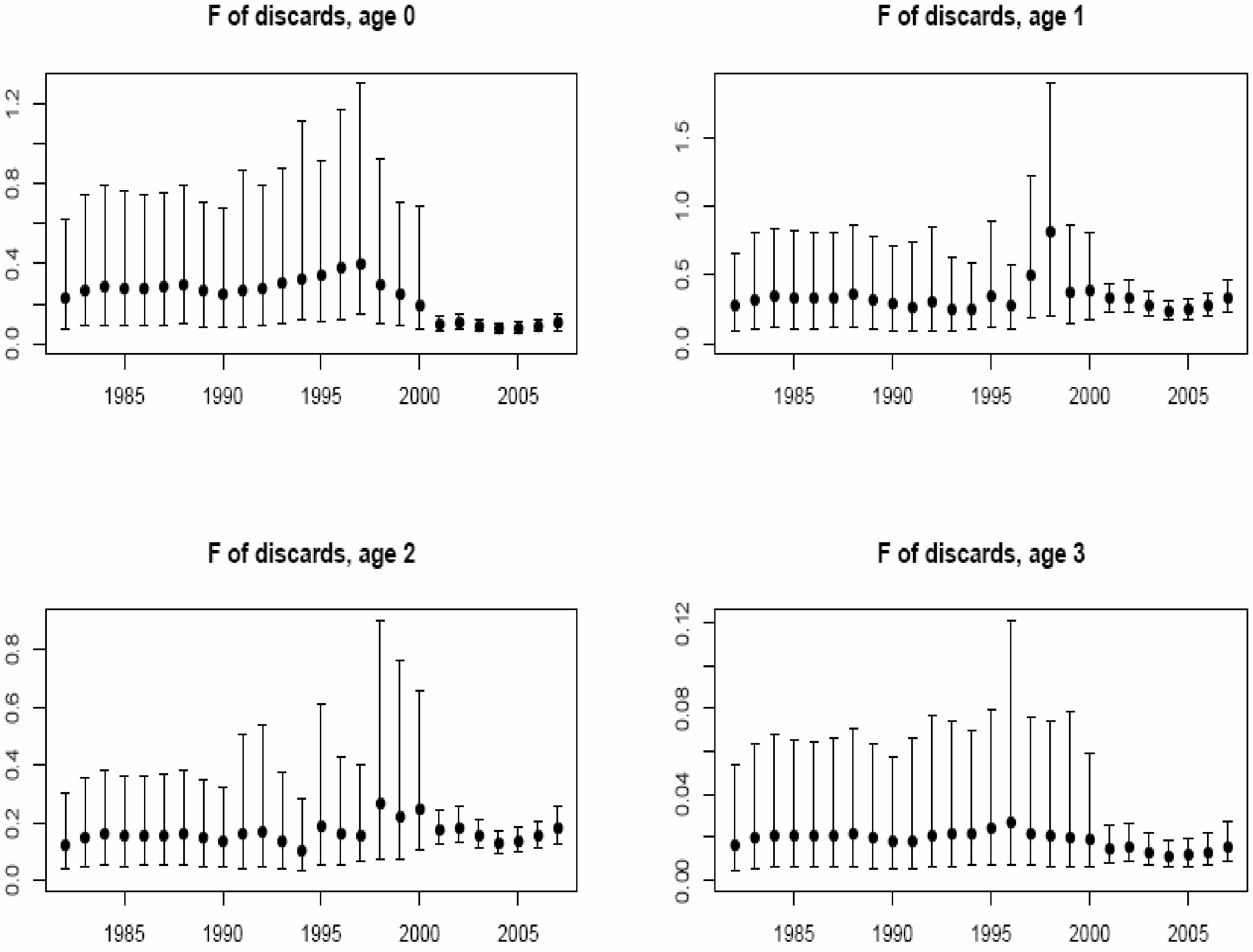

F(2007,0)/Fbar(2007)
0
5
10
15
0.0
0.2
0.4
0.6
0.8
1.0
F(2007,1)/Fbar(2007)
0
10
20
30
40
0.0
0.2
0.4
0.6
0.8
1.0
F(2007,2)/Fbar(2007)
0
2
4
6
0.4
0.6
0.8
1.0
F(2007,3)/Fbar(2007)
0
1
2
3
4
5
1.0
1.2
1.4
1.6
F(2007,4)/Fbar(2007)
0
1
2
3
4
5
0.7
0.8
0.9
1.0
1.1
1.2
1.3
F(2007,5)/Fbar(2007)
0
1
2
3
4
5
0.8
1.0
1.2
1.4
F(2007,6)/Fbar(2007)
0
1
2
3
4
0.8
1.0
1.2
1.4
1.6
F(2007,7)/Fbar(2007)
0.0
1.0
2.0
1.0
1.5
2.0
2.5
F(2007,8+)/Fbar(2007)
0.0
0.4
0.8
1.2
0.5
1.0
1.5
2.0
2.5
3.0

Fig. 3



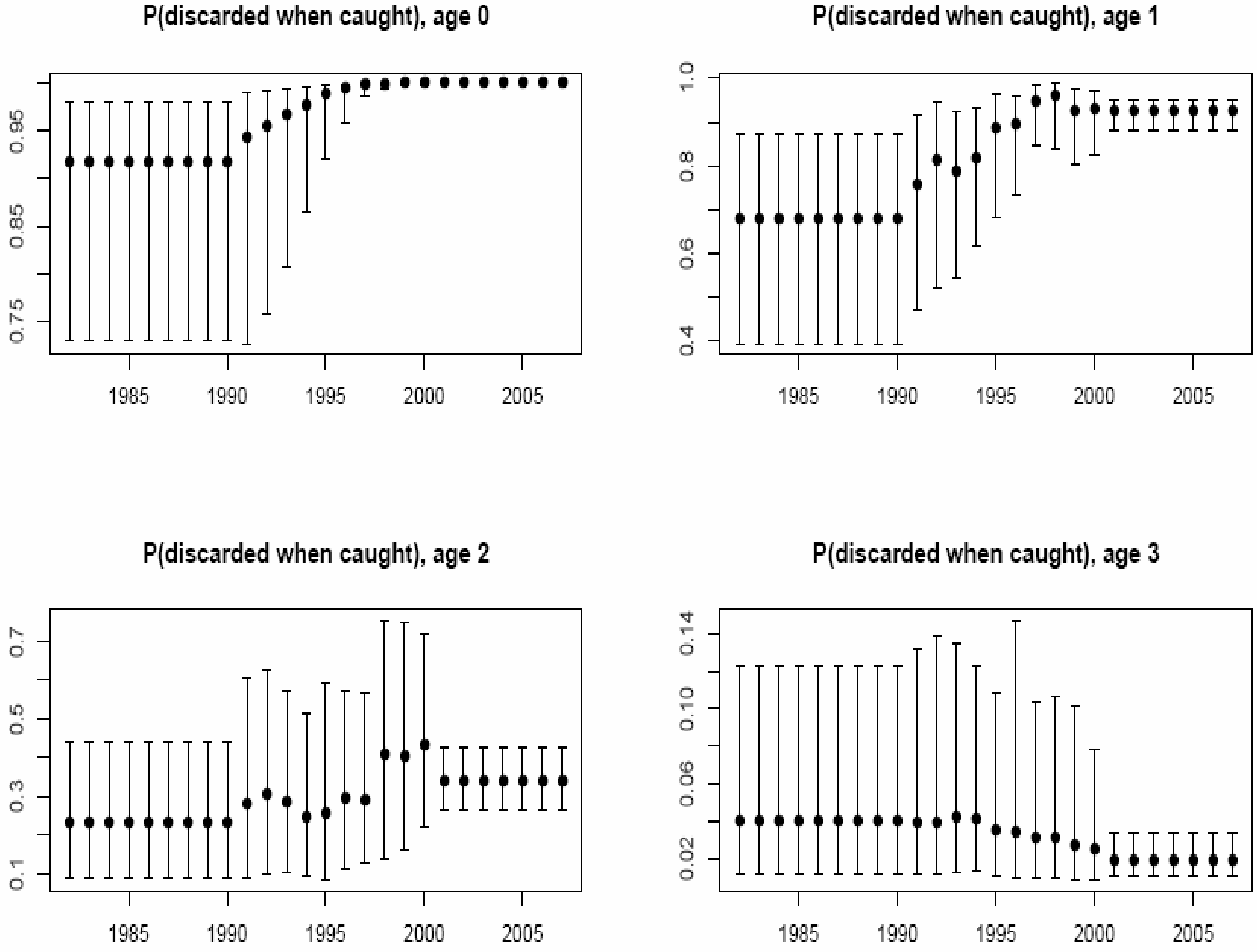
F of discards, age 0

F of discards, age 1

F of discards, age 2

F of discards, age 3

Fig. 4

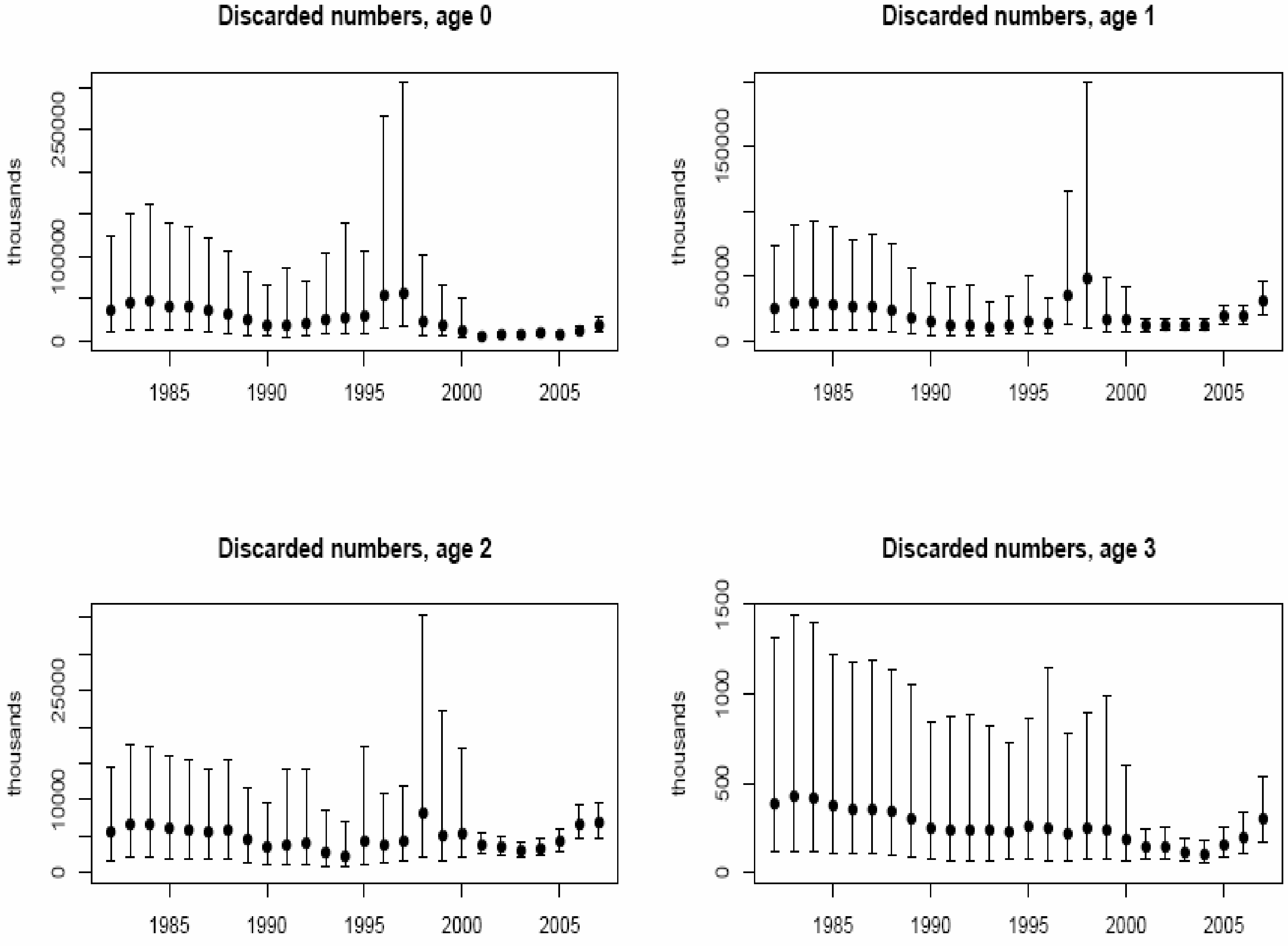

P(discarded when caught), age 0

P(discarded when caught), age 1

P(discarded when caught), age 2

P(discarded when caught), age 3

Fig. 5



Discarded numbers, age 0

Discarded numbers, age 1

Discarded numbers, age 2

Discarded numbers, age 3

Fig. 6

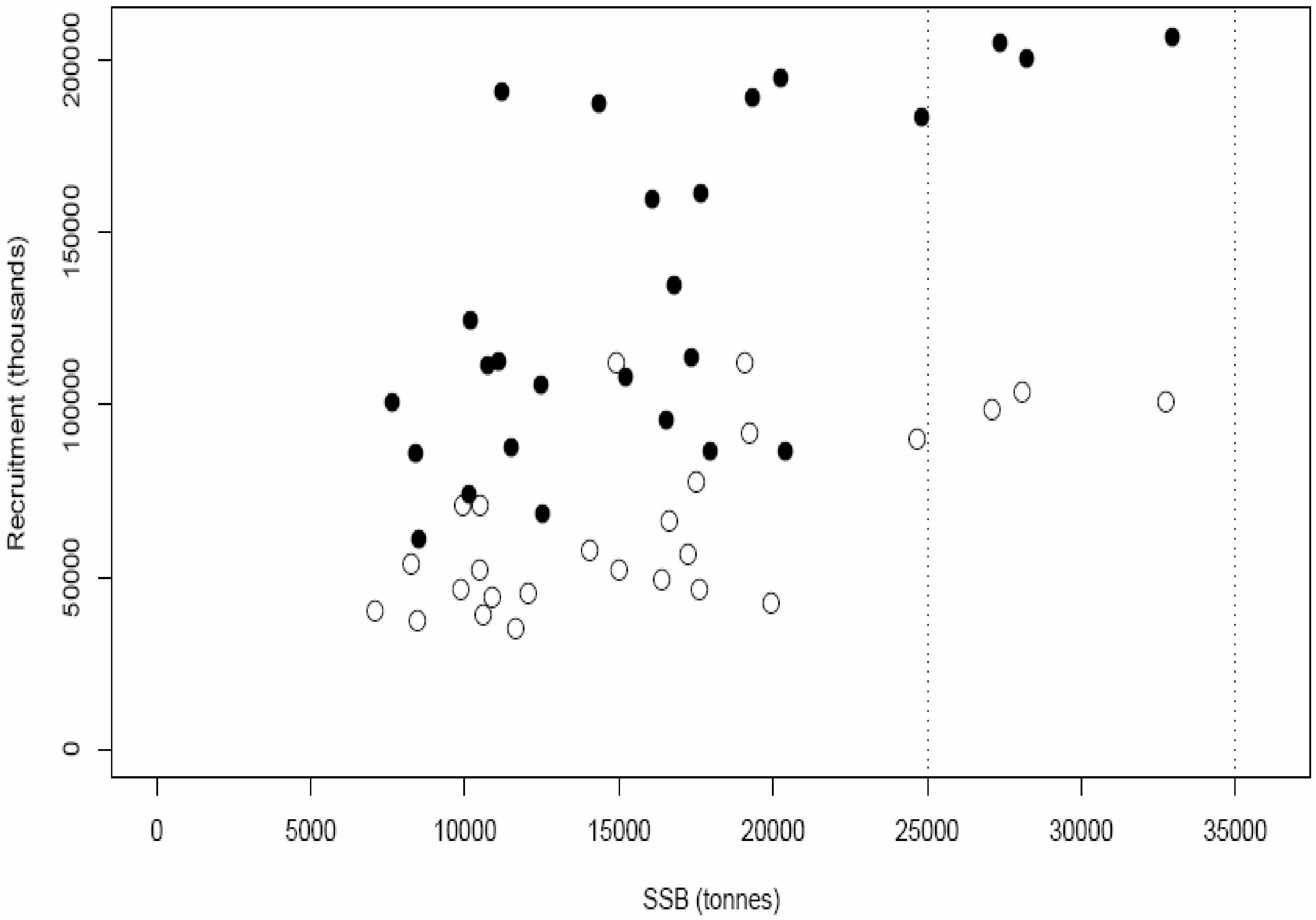

Recruitment (thousands)
0
50000
100000
150000
200000
0
5000
10000
15000
20000
25000
30000
35000
SSB (tonnes)

Fig. 7

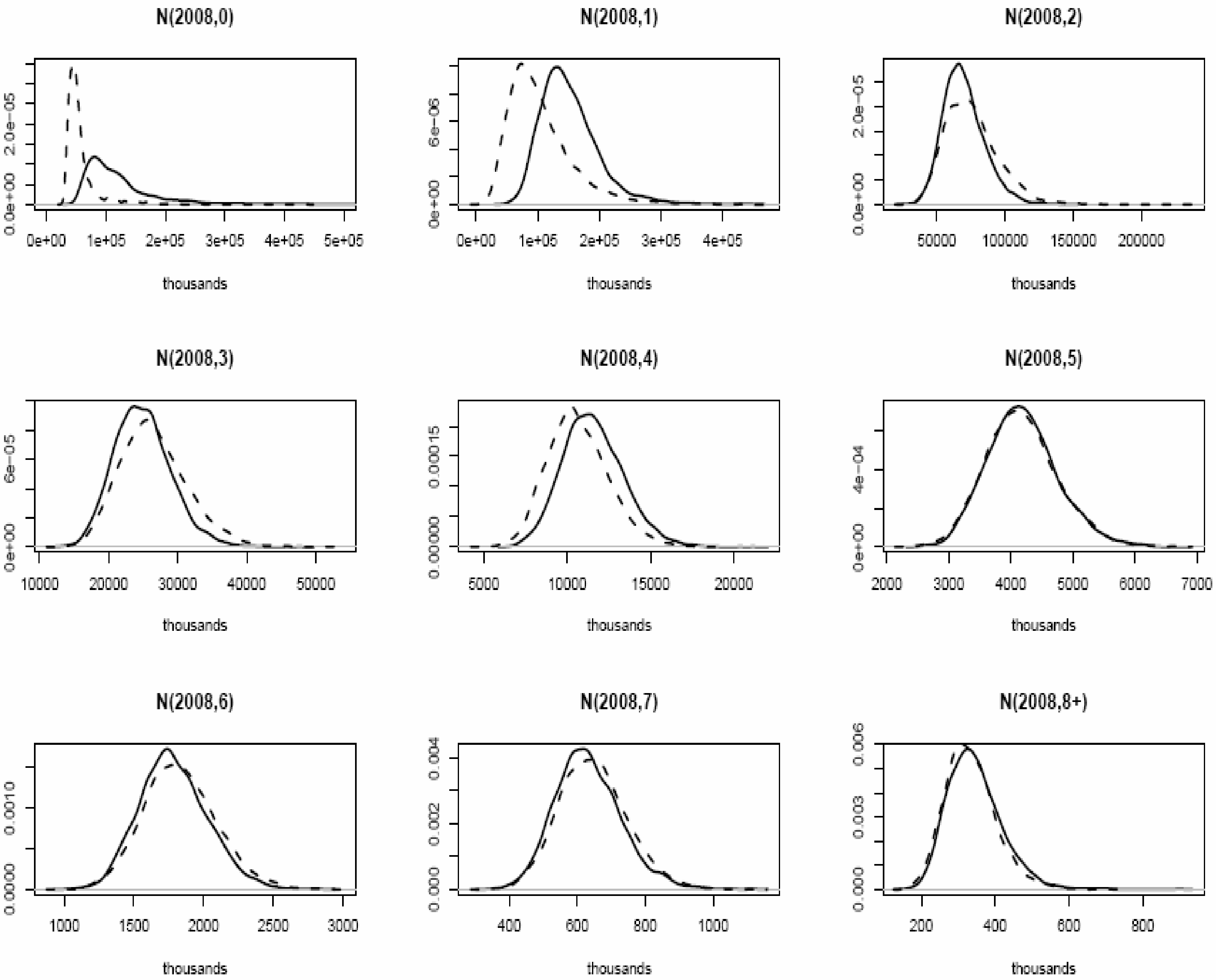
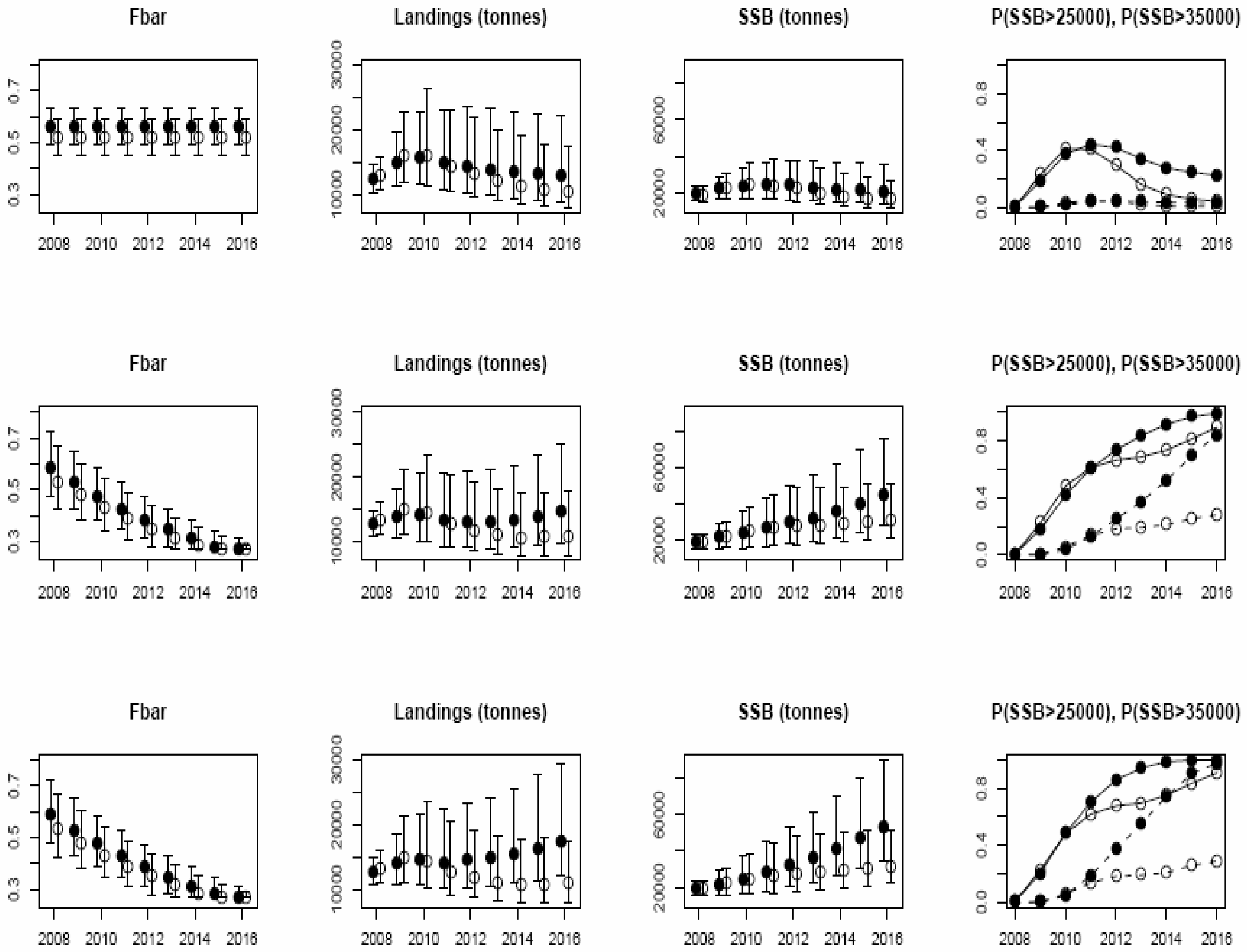

N(2008,0)
0.0e+00
2.0e−05
0e+00
1e+05
2e+05
3e+05
4e+05
5e+05
thousands
N(2008,1)
0e+00
6e−06
0e+00
1e+05
2e+05
3e+05
4e+05
thousands
N(2008,2)
0.0e+00
2.0e−05
50000
100000
150000
200000
thousands
N(2008,3)
0e+00
6e−05
10000
20000
30000
40000
50000
thousands
N(2008,4)
0.00000
0.00015
5000
10000
15000
20000
thousands
N(2008,5)
0e+00
4e−04
2000
3000
4000
5000
6000
7000
thousands
N(2008,6)
0.0000
0.0010
1000
1500
2000
2500
3000
thousands
N(2008,7)
0.000
0.002
0.004
400
600
800
1000
thousands
N(2008,8+)
0.000
0.003
0.006
200
400
600
800
thousands

Fig. 8


Fbar
Landings (tonnes)
SSB (tonnes)
P(SSB>25000), P(SSB>35000)
0.3
0.5
0.7
10000
20000
30000
20000
60000
0.0
0.4
0.8
2008
2010
2012
2014
2016