Comprehensive discard reconstruction and abundance estimation using flexible selectivity functions

G. Aarts and J. J. Poos

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The additional mortality caused by discarding may hamper the sustainable use of marine resources, especially if it is not accounted for in stock assessment and fisheries management. Generally, long and precise time-series on age-structured landings exist, but historical discard estimates are often lacking or imprecise. The flatfish fishery in the North Sea is a mixed fishery targeting mainly sole and plaice. Owing to the gear characteristics and a minimum landing size for these species, considerable discarding occurs, especially for juvenile plaice. Discard samples collected by on-board observers are available since 1999 from a limited number of commercial fishing trips. Here, we develop a statistical catch-at-age model with flexible selectivity functions to reconstruct historical discards and estimate stock abundance. We do not rely on simple predefined selectivity ogives, but use spline smoothers to capture the unknown non-linear selectivity and discard patterns, and allow these to vary in time. The model is fitted to the age-structured landings, discards, and survey data, the most appropriate model is selected, and estimates of uncertainty are obtained.

Keywords: discards, North Sea, plaice, population dynamics, splines, statistical models.

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Introduction

Discarding is the practice of returning an unwanted section of the catch back to the sea during fishing operations. Discards not only include non-commercial species, but also commercial species that are below minimum landing size (MLS) or less profitable owing to market conditions and quota restrictions (Catchpole *et al.*, 2005). Most of the fish that are discarded do not survive the catching and sorting process (van Beek *et al.*, 1990; Kaiser and Spencer, 1995). This additional mortality may hamper the sustainable use of marine resources, especially if it is not accounted for in fisheries management (Alverson *et al.*, 1994, Crowder and Murawski, 1998, Rijnsdorp *et al.*, 2007).

Accounting for discards in the exploitation of fish stocks starts with their estimation and use in stock assessment. Discard surveys in recent years reveal that discards may correspond to a substantial part of the catch, and for some stocks, they may even exceed the landings (ICES, 2008). However, the existing discard estimates often cover a small fraction of the fleet and may therefore be imprecise.

Punt *et al.* (2006) developed a flexible, statistical catch-at-age model that incorporates discard estimates into stock assessment. The method also facilitates discard reconstruction for years lacking discard data, assuming that discard selectivity is constant in time, but what if fishing and discard selectivity-at-age changed over time? Here, we propose an alternative method for estimating discards and assessing the demographic state of the population. The method is based on a statistical catch-at-age model (Fournier and Archibald, 1982; Deriso *et al.*, 1985; Gudmundsson, 1994; Fryer, 2002; Punt *et al.*, 2006). Spline smoothers are used to capture the unknown non-linear selectivity and discard patterns, using only few parameters. Hence, we do not have to rely on simple predefined shapes for this important fishing process. By making the parameters in the spline smoothers dependent on time, the method is also able to deal with time-variant selectivity and discard patterns. An additional advantage of statistical catch-at-age models is that both parameter estimates and standard errors for these estimates can be provided. Hence, the uncertainty in the stock development estimate can be shown and be used in managing the fisheries. Finally, the maximum likelihood estimation of the model parameters makes it possible to use information criteria as an objective way to compare models.

We apply the statistical catch-at-age model using landings, discards, and scientific survey data for North Sea plaice (*Pleuronectes platessa*). This species is caught in the North Sea demersal flatfish fishery, which is a mixed fishery targeting a range of flatfish species (Daan, 1997; Poos and Rijnsdorp, 2007). Changes in market conditions, costs of fishing, or management measures such as the establishment of the "plaice box" (Pastoors *et al.*, 2000; Dinmore *et al.*, 2003) have led to changes in gear efficiency and seasonal and spatial dynamics of the fleets. In particular, the Dutch beam trawl fishery has seen a displacement of fishing effort from the northern to the southern North Sea (Quirijns *et al.*, 2008), the latter characterized by higher concentrations of sole (*Solea solea*), but also juvenile plaice. The small mesh sizes necessary to fish for sole combined with an MLS for plaice of 27 cm leads to considerable discarding of mostly juvenile plaice (van Beek, 1990; van Keeken *et al.*, 2004).

An extensive scientific discard sampling programme using on-board observers was initiated in 1999 (van Keeken *et al.*, 2004). The programme estimates discards from several fish stocks in the countries around the North Sea. Because of the high costs of these observer programmes, sampling effort in the individual countries is generally low compared with the number of fishing trips. For the years preceding the observation programme, discards were estimated following a slight modification of the approach of Casey (1996). This approach is based on prerecruit growth rates, selectivity characteristics of the fishery, and XSA (Shepherd, 1999) estimates of fishing mortality (van Keeken *et al.*, 2004; ICES, 2005). Not only is this method criticized for its conceptional complexity, but its deterministic approach also ignores uncertainty. In the statistical catch-at-age model proposed here, the reconstruction of both historical discards and stock development are estimated consistently and concurrently.

Methods

Data

Landings, discards, and survey tuning data for North Sea plaice were available from ICES (2008). The combined landings-at-age data from different countries were available from 1957 on, spanning ages 1–15. Discard estimates were available for the period 2000–2007, containing samples from the Netherlands, Denmark, and the UK. There was a marked difference between the spatial distribution of the fishing effort of those countries' fleets. This difference causes different age structures in the landings and discards, because of the spatial distribution of juvenile and adult plaice, and because of the different mesh-size regulations that apply in different areas of the North Sea. The tuning index data were available from three surveys: (i) BTS-Isis, (ii) BTS-Tridens, and (iii) SNS (Rogers *et al.*, 1997). These surveys take place in different areas of the North Sea in the third quarter of the year. Because of the large number of zero observations in the survey data for ages 10+, only data for ages 1–9 were used. However, the discards were only estimated for ages 1–8, because all data at age 9 or older were zero. Likewise, because of the limited survey data availability before 1985 for ages 4–9, the estimation model is constructed from 1980 on, such that at least part of the earliest cohorts was covered by the survey data at older ages.

Model description

The model is a traditional discrete-time age-structured population dynamics model

$$N_{a+1,t+1} = N_{a,t}\mathrm{e}^{-Z_{a,t}}, \tag{1}$$

where $N_{a,t}$ are the numbers at age a at time t, and $Z_{a,t}$ the total mortality, which is composed of the instantaneous natural mortality rate M and the fishing mortality rate $F_{a,t}$.

Natural and fishing mortality

Natural mortality is assumed to be constant (0.1) in time and equal for all ages. Fishing mortality $F_{a,t}$ is the result of catchability q, annual fishing effort e_t, and the selectivity pattern $f_{a,t}$, such that

$$F_{a,t} = qe_t f_{a,t}. \tag{2}$$

Catchability q is the extent to which a stock is susceptible to fishing. The fishing effort e_t is the total amount of fishing in a year, and varies each year (hence the subscript t). With the available data, it is only possible to estimate the product of these two. The selectivity pattern $f_{a,t}$ defines the relative likelihood that an individual of age a in the population is caught and is constrained to have a maximum of 1. This age-dependent selectivity is the result of several processes. First, younger fish are generally smaller, and more likely to escape through the meshes of the net. In contrast, older fish may be able to avoid being caught, e.g. by outswimming the gear. Finally, age-specific differences in the spatial and temporal overlap between the fish and fishery influence the probability of individuals coming into contact with the fishing gear, affecting the selectivity pattern. The above processes make the fishing selectivity a complex function of age, and specifying an *a priori* shape may not fully address the multitude of processes that take place in shaping its functional form. Therefore, we used a smooth function of age, constructed using four b-spline basis functions $h_k(a)$ (de Boor, 2001). These functions can be viewed as four transformations of the explanatory variable a. Each b-spline basis function is a cubic polynomial of the explanatory variable, but it is only non-zero within a certain range (defined by so-called knots) of the explanatory variable. Next, each basis function $h_k(a)$ is weighted by a constant $b_{k,t}$. Summing these weighted functions results in the complex smooth function of age:

$$f_{a,t} = \mathrm{logit}^{-1}\left(\sum_{k=1}^{4} b_{k,t}h_k(a)\right). \tag{3}$$

In this function, logit^{-1} is $\exp(\cdot)/(1+\exp(\cdot))$ and ensures that $f_{a,t}$ takes values between 0 and 1. One could also use a polynomial function of age. However, because of the local nature of the basis function, the fit of the smooth function in one range of the data (e.g. at low ages) is independent of its fit at the other extreme (e.g. at high ages). Similar to many other assessment techniques, we assume that the fishing mortality of the last age class is equal to the fishing mortality of the preceding age. Temporal changes in the spatial overlap between fishing effort and the different age classes of the fish population can result in changes in the selectivity pattern. This is captured by modelling the weighting constants as a function of time, hence the subscript t in $b_{k,t}$. To prevent overparameterization, only a linear function for the temporal changes in selectivity was inspected, i.e.

$$b_{k,t} = \beta_{0,k} + \beta_{1,k}t. \tag{4}$$

Discards and landings

The expected catch $C_{a,t}$ for age a and year t is calculated from

$$C_{a,t} = \frac{F_{a,t}}{Z_{a,t}} N_{a,t}(1 - \mathrm{e}^{-Z_{a,t}}). \tag{5}$$

The catch consist of discards $D_{a,t}$ and landings $L_{a,t}$. We assume that an age-dependent fraction $d_{a,t}$ of the catch is discarded, such that

$$D_{a,t} = d_{a,t}C_{a,t}, \tag{6a}$$

$$L_{a,t} = (1 - d_{a,t})C_{a,t}. \tag{6b}$$

Although landings data are generally available, discard data are often lacking or, as in our study, only available for the most recent years.

Several model formulations for the discard fraction $d_{a,t}$ are fitted and compared: (i) a linear function of age on the logit scale assuming a time-invariant discard pattern:

$$d_{a,t} = \text{logit}^{-1}(\beta_0 + \beta_1 a), \tag{7}$$

(ii) a time-invariant smooth function of age [similar to Equation (3)], (iii) a smooth function of age that varies linearly in time [similar to Equations (3) and (4)], and (iv) a smooth function of age where each smooth parameter [see Equation (4)] is modelled as a second-order orthogonal polynomial function of time. The mathematical form of the orthogonal polynomial can be found in Ismail (2005), and its implementation in R is described in Chambers and Hastie (1992).

Survey tuning series

The tuning series data for plaice are collected over a short period (August–September) of each year. Because the survey vessel catches are a very small part of the population, it is assumed that these catches do not affect the mortality of the population as a whole. The population size $N_{a,t}$ represents the population size on 1 January of year t. When the scientific survey takes place later in the year, the population size may be reduced considerably by fishing and natural mortality. To correct for this, the mean population size during the time of the survey $N^U_{a,t}$ is estimated as

$$N^U_{a,t} = N_{a,t}\frac{e^{-\kappa Z_{a,t}} - e^{-\lambda Z_{a,t}}}{(\lambda - \kappa)Z_{a,t}}, \tag{8}$$

where κ and λ are the start and end, respectively, of each survey expressed as a fraction of a year.

Consequently, the catch of survey $U_{a,t}$ of age a in year t can easily be calculated as

$$U_{a,t} = s_{u,a}N^U_{a,t}q_u, \tag{9}$$

where q_u is the efficiency, which is survey vessel u-specific, and $s_{u,a}$ the age-specific selectivity of the survey vessel u. Again, we model $s_{u,a}$ as a smooth function of age [similar to Equation (3)].

Survey selectivity $s_{u,a}$ is assumed to remain constant in time, based on the observation that the gear, the timing, and the spatial distribution of the scientific surveys have not changed.

Likelihood function

The available datasets for parameter estimation are (i) landings-at-age, (ii) discards-at-age, and (iii) tuning series from three surveys. Conforming with most other statistical catch-at-age assessment methods (Fournier and Archibald, 1982; Deriso *et al.*, 1985; Gudmundsson, 1994; Fryer, 2002, Punt *et al.*, 2006), the data are assumed to be lognormally distributed, with means and age-specific standard deviations predicted by the model. Visual inspection of the residuals indicated that they were approximately normally distributed. There were five zero values in a total of 715 observations in the three datasets. These zero values were replaced by half of the lowest value observed in the dataset where each occurred. This approach guards against zeros in the likelihood function by taking account of the scale of the data. The total log-likelihood ℓ is then

$$\begin{aligned} \ell &= \ell_D + \ell_L + \ell_U, \\ \text{where } \ell_D &= \sum_{a,t} \text{n}(\log(D_{a,t}); \log(\hat{D}_{a,t}), \sigma^D_a), \\ \ell_L &= \sum_{a,t} \text{n}(\log(L_{a,t}); \log(\hat{L}_{a,t}), \sigma^L_a), \\ \ell_U &= \sum_{a,t} \text{n}(\log(U_{a,t}); \log(\hat{U}_{a,t}), \sigma^U_a). \end{aligned} \tag{10}$$

Here, $\text{n}(\log(D_{a,t});\log(\hat{D}_{a,t}),\sigma^D_a)$ is the normal probability density of the log of the observed values $D_{a,t}$, with mean $\log(\hat{D}_{a,t})$ and standard deviation σ^D_a. Residual plots for the initial model runs suggested that the variability in the residuals differed with age. To capture this effect, the values of σ_a are modelled as the exponent of an orthogonal polynomial function of age, with 2 d.f. (Chambers and Hastie, 1992). The standard deviations are constrained to be at least 0.05, to facilitate convergence of the minimizer used to find the maximum likelihood.

Parameter estimation and model selection

All model fitting was done in R (R Development Core Team, 2008), using the FLR package (Kell *et al.*, 2007). The negative of the likelihood function in Equation (10) was minimized using the Broyden–Fletcher–Goldfarb–Shanno (BFGS) quasi-Newton or variable metric algorithm. Several starting values were selected randomly from a uniform distribution within appropriate boundaries, leading to different parameter estimates. This suggests that the likelihood function had several local maxima. We therefore selected the parameter estimates corresponding to the highest maximum likelihood among multiple runs (>50 times). The model often converged to these parameter estimates, and we assumed that these correspond to the global maximum. Also, all eigenvalues of the numerically differentiated Hessian matrix at the parameter values presented here were positive, indicating that the parameter values indeed represented a maximum of the log-likelihood function.

Models with different fishing and discard selectivity functions described above were fitted to the data. The Akaike Information Criteria (AICs) of the model fits were compared, and the model with the lowest AIC was retained for further analysis and inference of the population dynamics and abundance. However, different functional forms of the different model assumptions with respect to selectivity and discarding patterns are presented too, to explore the effect of different model assumptions on these patterns.

Quantifying uncertainty

Minimizing the negative of Equation (10) results in maximum likelihood parameter estimates and the variance–covariance matrix that is derived from the inverse of the Hessian. For estimating parameter uncertainty, we selected random values (10 000) from a multivariate normal distribution with those parameter means and variance–covariances. The resulting random realizations are then used to estimate 95% confidence intervals for population and fisheries characteristics of interest, using the percentile method.

Results

Selectivity functions

As a reference, the full model containing both a time-variant fishing and discard selectivity function was fitted first. The AIC of this model (862; see Table 1) was compared with a model with time-invariant fishing and/or different discard selectivity functions. Based on the AIC, the full model (with time-variant fishing and discard selectivity described by a polynomial time-variant spline) outperformed the simpler models. This model will be used for further comparison and inference.

The best fitting model for the fishery on North Sea plaice has a slightly dome-shaped selection curve, with fishing mortality highest on ages 3 and 4. This is similar for the models with a time-variant and a time-invariant fishing selectivity pattern (Figure 1). Clearly, there has been a trend to exploit the older ages less in recent years, and the selection pattern is lower for ages 6+ . These model estimates corroborate the southward shift in the spatial distribution of the fishery, increasing its overlap with the younger ages of plaice. The time-variant discarding model indicates an increase in selectivity for the young ages (ages 1 and 2) in the most recent years.

The discard fraction is a decreasing function of age in all models (Figure 2). The discard fractions of the catch for each age changed little in time, but nevertheless significantly (based on AIC, see Table 1). The younger ages (ages 1 and 2) were discarded substantially (>80%). Our results suggest that a relative larger proportion of ages 4–7 was discarded in the early years (1985). Although the discard fraction at age may have been relatively stable in time, the absolute levels of discards have not, because the amount of discarding also depends on the age-specific selectivity pattern, fishing effort, and population size. Changes in any one of these, such as the observed changes in fishing selectivity, will directly influence the observed discards.

The selectivity curves for the surveys are key in estimating fishing mortality and discarding in the period where only landing data were available. Both BTS-Isis and SNS surveys showed declining catchability with age, but for BTS-Tridens, it was increasing (Figure 3). The BTS-Isis and BTS-Tridens surveys use a similar gear and take place at the same time of year. Hence, the estimated large difference in catchability at age was most likely caused by the survey location. The BTS-Isis survey is closer to shore, whereas the BTS-Tridens is more offshore. The SNS survey is a coastal survey, sampling mainly 1- and 2-year-old fish. For older ages (6+ years), the BTS-Tridens, showed different patterns in catchability depending on whether a time-variant or time-invariant discard selectivity model was fitted. This indicates that there was either strong cross-correlation with other stock or fishery characteristics, or that there were insufficient data to support the functional form of the tuning catchability curves for these older ages.

Model residuals

The residuals for landings, discards, and the tuning series indicated how well the assumed population dynamics, model fitted the data.

The residuals for the estimated landings are larger in the very young animals (Figure 4). Also, for age 1, there are large negative residuals for 1987 and 1988 in the landing estimates, corresponding to the years where the original data contain zero values. All

Table 1. Model selection; model number, description of fishing and discards selectivity curves, and log-likelihood (LogL).

Model	Selectivity	Discarding	−LogL	P	Obs	AIC
1	Time-variant spline	Polynomial time-variant spline	318.8	112	715	**862**
2	Time-variant spline	Time-variant spline	333.6	108	715	883
3	Time-variant spline	Time-invariant spline	346.5	104	715	901
4	Time-variant spline	Time-invariant linear function	375.2	102	715	954
5	Time-invariant spline	Polynomial time-variant spline	325.0	108	715	866
6	Time-invariant spline	Time-variant spline	346.1	104	715	900
7	Time-invariant spline	Time-invariant spline	371.2	100	715	942
8	Time-invariant spline	Time-invariant linear function	402.8	98	715	1 002

The number of model parameters (*P*), the total number of observations (Obs), and the AIC are also given. The lowest AIC value is emboldened.

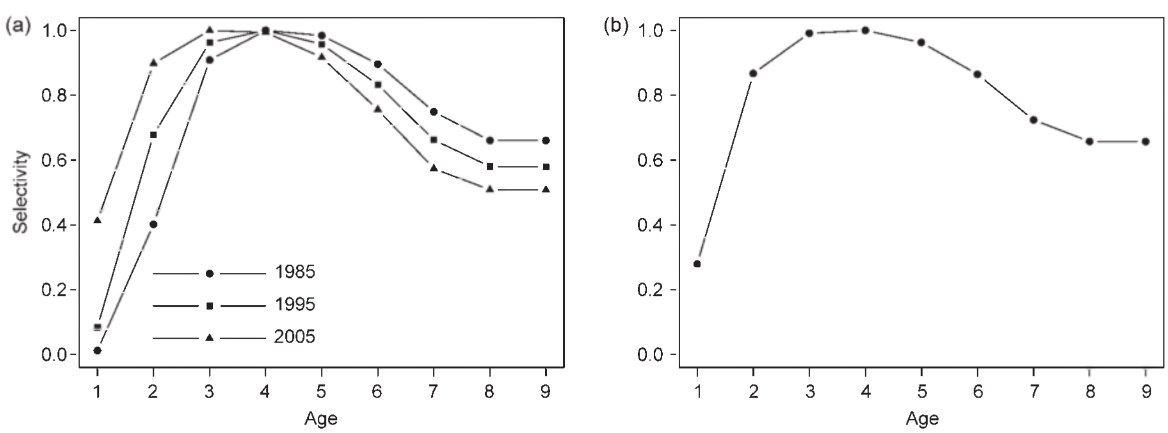

Figure 1. Selectivity of the catch for three different years (1985, 1995, and 2005) based on (a) the time-variant (Model 1 in Table 1), and (b) time-invariant (Model 5 in Table 1) fishing selectivity models.

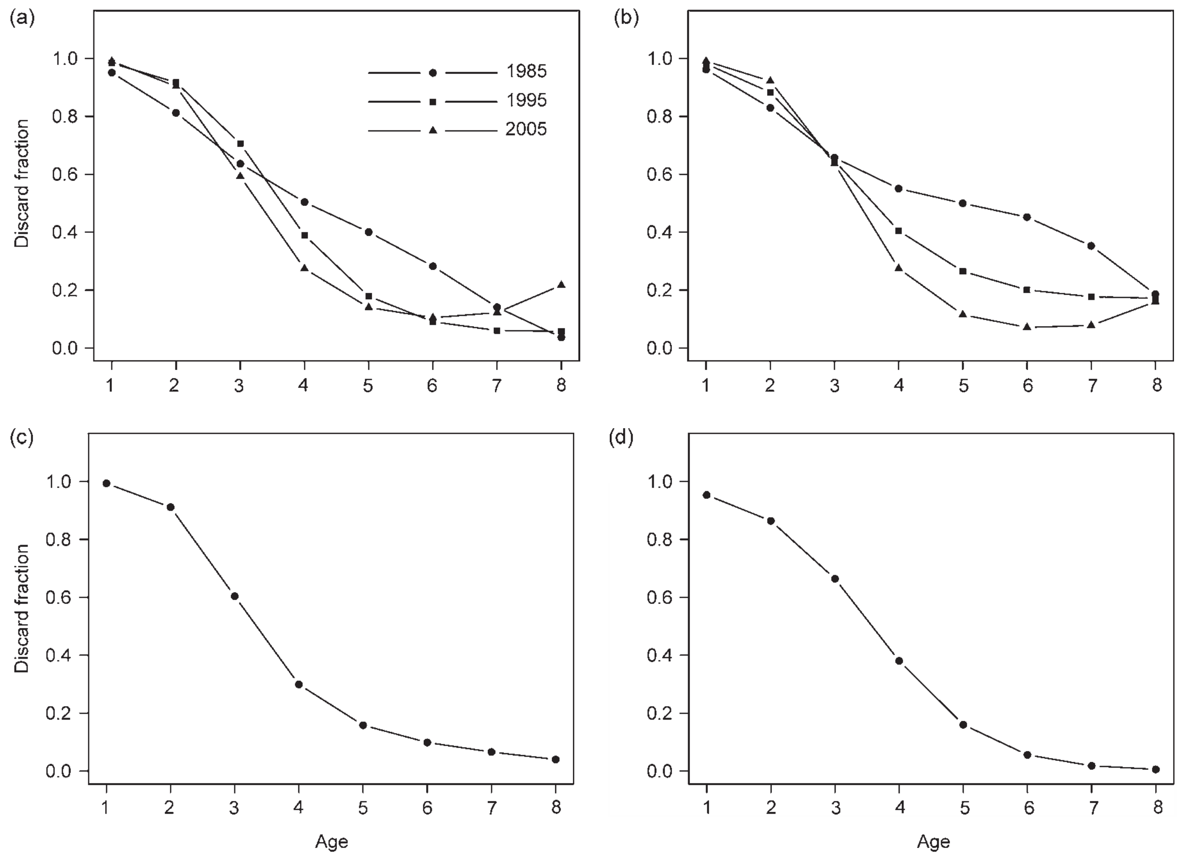

Figure 2. Fitted discard selectivity functions based on (a) a polynomial time-variant spline model (Model 1 in Table 1), (b) a linear time-variant spline model (Model 2 in Table 1), (c) a time-invariant spline model (Model 3 in Table 1), and (d) a time-invariant model where the discarding is a linear function of age on the logit scale (Model 4 in Table 1).

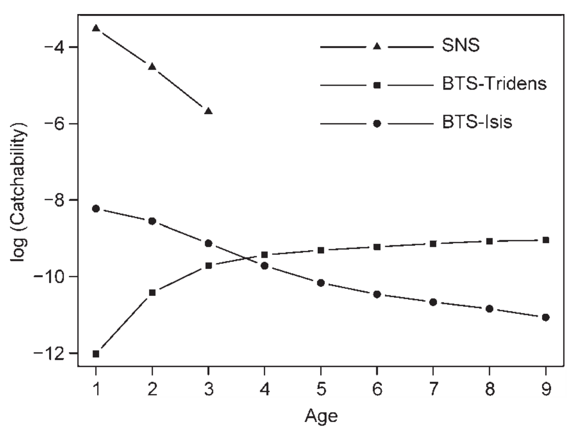

Figure 3. Estimated catchabilities of the three surveys (SNS, BTS-Tridens, and BTS-Isis) based on the full time-variant discard and fishing selectivity model (Model 1).

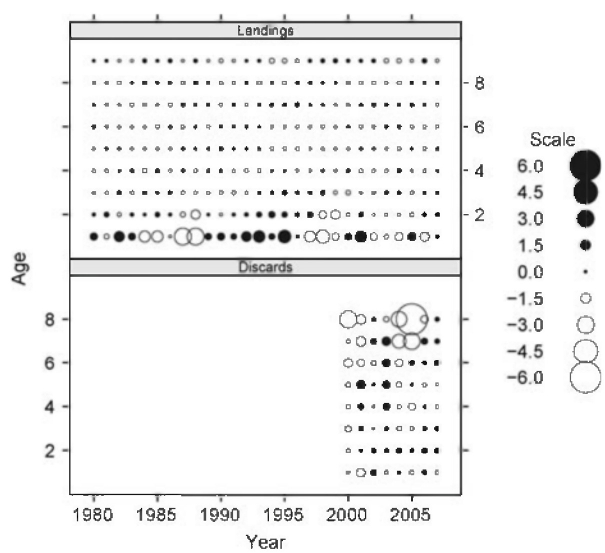

Figure 4. Log-residuals of landings and discard for the full time-variant fishing and discard selectivity model (Model 1).

other ages seem to have random residual patterns. The residuals of the discard estimates are generally larger than those of the landings, especially for older ages. Only for very young ages are the discard residuals smaller than the landings residuals. The large difference in the residuals by age may be caused by the low discard estimates for the older ages. The model also shows a tendency to have positive residuals in discard estimates for age 2 that may be caused by insufficient flexibility to model the discard pattern over ages. This results in an underestimation of discards at age 2 while fitting the model according to other ages.

A striking pattern in the survey residuals (Figure 5) is the abrupt change in the SNS residuals in 2000, which were

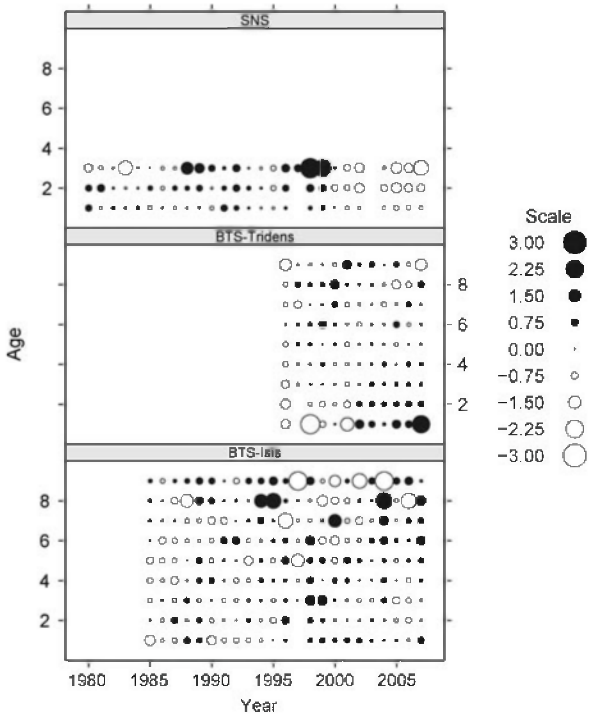

Figure 5. Log-residuals of the survey indices for the full time-variant fishing and discard selectivity model (Model 1).

consistently lower than model expectations, resulting in negative residuals for all ages. In the same period, BTS-Tridens indices observed for ages 1–3 were consistently higher than the expected juvenile population. This resulted in positive residuals for those ages since 2000.

Population and fishery summaries

The summary plots of the historical population dynamics (Figure 6) show that the estimated landings increased up to 1988, after which a steep decline took place. Another striking aspect is that the model closely fits the data, which is also supported by the uncertainty estimates being very small, especially for the most recent years. The estimated discards in the most recent years match those of the actual observations reasonably well, but there seems to be some underestimation. Except the discard peak that coincides with the high recruitment in 1986, the model estimated higher discards in the historical part of the time-series than the reconstruction used by the ICES Working Group. Notably, the lows in the reconstructed discards around 1994 were not supported by our stock assessment model estimates. The uncertainty of the total discarding estimate was several times larger at the beginning of the time-series than the most recent estimates. Recruitment showed very similar patterns between the different models, with strong recruitment in 1986, 1997, and 2002. Except for those peaks, there was a clear overall decline from the 1980s on. The mean fishing mortality of ages 2–6 increased up to 1997, after which there was a steep decline.

Spawning–stock biomass (SSB) estimates were high in the 1980s and declined in the 1990s. This resulted from the higher recruitment in the 1980s, combined with a fishery that targeted older individuals. After a low in 1997, SSB appeared to be slightly increasing again, and it is currently fluctuating around 220 000 t.

As a result of the uncertain discard estimates at the beginning of the time-series, the uncertainty of the SSB estimates at the same time was larger than the uncertainty towards the end of the time-series.

Overall, the results correspond to the results of the XSA assessment done by the ICES Working Group, except the fishing mortality in most recent years. The model presented here indicates a strong decline in fishing mortality to ~0.3 in 2007, whereas the latest ICES estimate (for 2007) is 0.39. It should be noted that the uncertainties presented here are conditional on model formulation and do not incorporate model uncertainty.

Discussion

The results of this study provide estimates of historical discarding and stock development of North Sea plaice. The estimates are based on fitting a simple age-structured population dynamics model to landings, discards, and survey indices. The estimation of missing discard values was integrated with the assessment of the demographic state of the population. Using an information criterion (AIC), different assumptions on trends in selectivity pattern were tested, preventing the formulation of an overly complex model that was not supported by the data (Cotter *et al.*, 2004).

Our model differs from alternative approaches in the literature. Casey (1996) used a mechanistic approach to estimate discards using landings-at-age data from the fishery, together with species-specific mesh selectivity parameters, assuming that the size distribution in the population was known or could be inferred. Those discard estimates were subsequently used in a VPA stock assessment. The method was developed for a situation in which absolutely no discard data were available, and in the absence of any information on discarding practices, it is assumed that the primary reason for discarding fish is to comply with MLS regulations. A second approach (Punt *et al.*, 2006) used a statistical catch-at-age model, similar to the approach presented here. Although more biological detail was incorporated in the population dynamics part of the model, gear selectivity was estimated using a logistic and a dome-shaped function (of length) and was assumed constant in time. This may suffice for many fisheries where selectivity patterns are constant, but in the North Sea demersal fleet, the selectivity pattern has changed owing to changes in the spatial distribution of the fleet, e.g. with the establishment of the “plaice box” (Pastoors *et al.*, 2000).

The statistical catch-at-age model used here considers four types of discard selectivity pattern. Discard selectivity was modelled as a linear function of age, or as a more flexible function of age, with two functions allowing discard fractions to change over time. Our results indicated a sharp decline of discarding with age. This is due to the MLS for plaice resulting in discarding individuals <27 cm (Daan, 1997), which in general will be the younger fish. The discard-at-age curve for the time-variant discard models suggested that, historically, adults in the mid-range of the age distribution were discarded more frequently. Indeed, discarding patterns may have been different in the past because of different MLS values, different growth, different spatial distributions of fish (van Keeken *et al.*, 2007), or market conditions (Rochet and Trenkel, 2005). Although highgrading was most likely higher from the 1960s until the early 1970s, it is not a likely explanation for our bigger discard estimates of subadults in the 1980s (Rijnsdorp *et al.*, 2008).

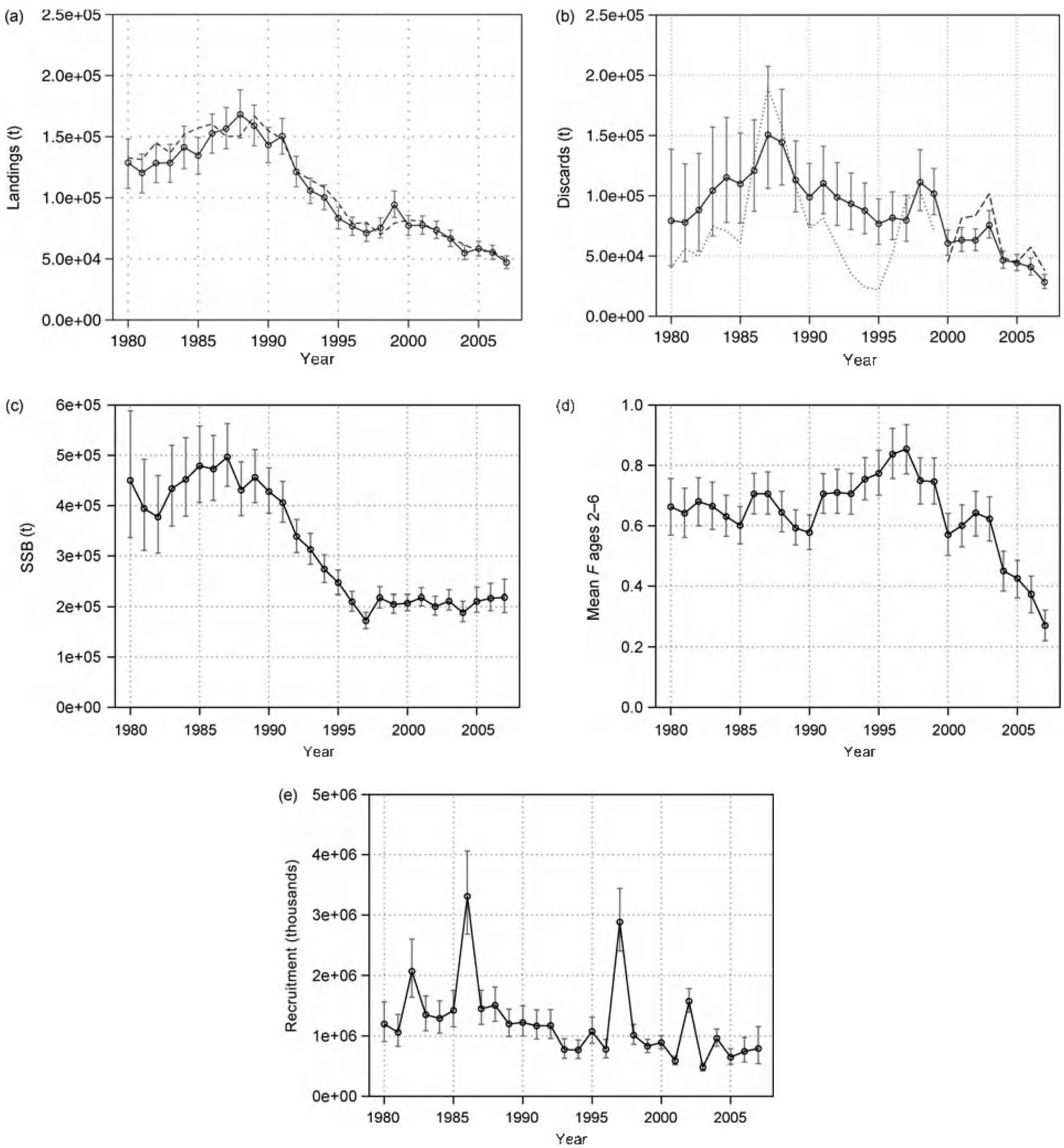

Figure 6. Model estimates (95% confidence intervals): (a) landings, (b) discards, (c) SSB, (d) mean fishing mortalities at ages 2–6, and (e) recruitment for the full time-variant fishing and discard selectivity model (Model 1). The dashed lines in panels (a) and (b) represent the landings and discard observations. The dotted line in panel (b) represents the current discard reconstruction used by the ICES Working Group on the Assessment of Demersal Stocks in the North Sea and Skagerrak.

The extent of discarding in a fishery does not only depend on the discard levels at age, but also on gear selectivity. Therefore, quantifying changes in gear selectivity over time is crucial to historical discard reconstruction. Our results show that the gear selectivity pattern changed over time. In more recent years, older fish were less likely to be caught than in the earlier period. Such changes in selectivity are in line with the redistribution of fishing effort. In recent years, fishing vessels came closer to shore to target sole (Quirijns *et al.*, 2008). These coastal regions are characterized by relatively larger numbers of juvenile plaice (Wimpenny, 1953; Rijnsdorp and van Beek, 1991). Indeed, the selectivity of 1-year-old fish has increased from a few per cent in 1980 to 0.4 of the maximum selectivity in 2000, and almost all will be discarded.

The discard estimates obtained from the time-variant discard model resemble the actual observations in the past 7 years. In contrast, the time-invariant discard selectivity model suggests lower-than-observed discarding in those years. This may suggest that discards-at-age were lower historically, depressing estimates for the most recent years, but this pattern is not reflected by the time-variant discard selectivity curve. Compared with the current reconstructed discards (van Keeken *et al.*, 2004), our estimates showed similar highs and lows (reflecting the level of recruitment in the preceding year), but the extremes levelled out and, overall, our historical discard estimates were higher. These differences may result from the fact that our approach did not take account explicitly of the observed changes in mean body growth of the cohorts, in contrast to the deterministic reconstruction. Highgrading alone will not account for this difference in discard levels, because the absolute discard levels are mostly driven by 2- and 3-year-old fish.

Can we accurately reconstruct historical discards? One of the major limitations with many stock assessment models is that different sources of mortality cannot be separated from each other. In the case presented here, natural mortality was set at a fixed value for all years and age classes, consistent with the ICES procedure that is used to estimate stock size. Although this may be a reasonable assumption for older ages that are susceptible to considerable fishing pressure, it is questionable whether the fixed natural mortality assumption will hold for the younger fish that constitute the discards. Variation in natural mortality can be caused by changes in predation pressure, because plaice can be preyed on by birds, fish, and seals (Leopold *et al.*, 1998). Also, unobserved additional fishing mortality may exist, in the form of unreported landings or fish escaping from the net (Sangster *et al.*, 1996). If no historical discard data are available, increases or decreases in these mortality rates will be ascribed to the reconstructed discards. When discussing the absolute levels of discards in time, this will be a problem, but for stock assessment purposes it may not. The ultimate objective is to quantify accurately the population processes such as mortality rate. As long as changes are quantified correctly and consistently, it may not matter whether discards are labelled inappropriately. Some historical discarding data exist, but these data cover only the Dutch beam trawl fleet, and have not been raised to the population level (van Beek, 1990).

This and other studies have shown that statistical catch-at-age models can make use of a wide variety of data sources (Fournier and Archibald, 1982; Deriso *et al.*, 1985; Gudmundsson, 1994; Fryer, 2002; Punt *et al.*, 2006). Incorporating additional model components is straightforward if they can be linked to data, and providing their effects are separable from other model components. For example, high fishing pressure has led to rapid changes in age at maturation and individual growth. Although most fishery processes (e.g. mesh size, selectivity ogives, MLS) operate on length, most stock assessments are only age-structured. Punt *et al.*, (2006) showed how length-related processes (e.g. the Bertalanffy growth equation) can easily be incorporated into statistical catch-at-age models. Although increasing model complexity can easily lead to loss in model parsimony (Cotter *et al.*, 2004), selecting a particular type of model does not need to be based on speculative theories, but it can be based on objective information criteria. An ability to include more biological and fishery-related processes and objectively test for their significance makes statistical catch-at-age models a useful tool to test biological hypotheses and further understand fish demography. Finally, the models do not only provide estimates of stock size, but they also estimate uncertainties, valid for the model and the data used. For fisheries with substantial discarding, the catch data from on-board sampling are prone to substantial uncertainty because of small sample sizes (Heales *et al.*, 2003). Model mis-specification and noisy data often lead to biased estimates of population size and fisheries characteristics, but their effect on uncertainties are still poorly understood (Dickey-Collas *et al.*, 2007). We noticed that the SSB estimates and their uncertainties varied considerably for different model specifications. Consequently, we believe that use and interpretation should go together with testing a large variety of different models, before they can be used for management purposes.

Statistical catch-at-age models have a large number of advantages, and one may wonder why they have not been used to their full advantage. Traditional statistical catch-at-age models often estimate an age-specific selectivity and implicitly assume that selectivity does not change over time. When this assumption is violated, one can estimate a selectivity pattern for different periods independently. When the biological and fishery processes are complex and poorly understood, we suggest using spline smoothers instead. They do not rely on *a priori* simple selectivity patterns, but allow for flexible fishing and discard selectivity that can change over time, using only a small number of parameters. Other stock assessment models, such as those described by Gudmundsson (1994), Lewy and Nielsen (2003), and Schnute and Richards (1995) have been successfully applied to the same problem. However, the current model was designed specifically for reconstruction of both historical discards and stock dynamics of plaice in the North Sea. It provides a basis for extension with additional biological processes, but it can also easily be adapted to estimate the development for other fish stocks where discarding plays a considerable role.

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