Inclusion of discards in stock assessment models

Alternative 1: Discarding as a process component of stock assessment models

Alternative 2: Incorporating size and bulk discarding in stock assessment models

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Abstract

A large portion of the catch in many stocks may comprise discards which need to be accounted for in assessments in order to avoid bias in estimates of fishing mortality, stock biomass and reference points. In age structured assessment models, discards are sometimes treated as a separate fleet or are added to the landings before fitting so that information about discard behavior and sampling error is lost. In this paper an assessment model is developed to describe the discard process with size as a covariate while retaining age structured population dynamics. Discard size selection, high grading and bulk dumping of fish at sea are modelled so that the temporal dynamics of the process can be quantified within the assessment. The model is used to show that discarding practices have changed over time in a range of Northeast Atlantic demersal fish. In some stocks there is a substantial increase in high grading and evidence for bulk discarding which can be related to regulatory measures. The model offers a means of identifying transient effects in the discard process that should be removed from both short-term forecasts and equilibrium reference point calculations.

Key words: Demersal fish, high grading, Northeast Atlantic, reference points, size selection

Introduction

Discards are a concern to fishery managers, stakeholders and the public. Kelleher (2005) estimated global discard rates in demersal finfish and flatfish trawl fisheries to be 21% and 39% respectively based on an earlier study by Alverson et al, (1994). . Apart from the catch of low value unwanted species, much of the discarded portion of the catch comprises small fish of the target stock resulting from imprecise size selection by the gear. Poor selectivity has traditionally been considered detrimental to the potential yield of the stock (Beverton and Holt, 1957) while biomass returned to the sea may disturb ecosystems by altering energy flows that favour scavenging species (Heath et al, 2014; Bicknell et al 2013; Tasker et al 2000). More recently the theory of balanced harvesting has placed discarding in a more positive light (Zhou, 2008; Garcia et al, 2012) though it has been questioned as a realistic theory (Froese et al 2016). At present, fishery managers seek to minimise discarding and many jurisdictions ban discarding on some form. Norway is often seen as an example and promotes this approach (Gullestad et al, 2015). Public opinion is also a major factor in pressure to reduce discards and in Europe a media campaign was a significant influence leading to the introduction of the “Landing Obligation” that requires all fish caught to be landed (Borges, 2015). The public interest in discards and the desire by managers to minimise them means that discards need to be explicitly considered in stock assessments.

In many fisheries the most easily observable part of the catch is the landings since it is the component brought ashore where samples can be obtained and quantities recorded. However, the discards are not readily observed. Where the discarded fraction is not accounted for in the catch data used in assessments, bias can result both in the estimation of exploitation rates and stock biomass (Punt et al, 2006; Dickey-Collas, 2007). This in turn can affect the calculation of reference points used to manage the stock. Where discards form a substantial fraction of the catch it is therefore important to account for this in the assessment model.

Since most exploited fish populations have over-lapping generations, models used in assessment generally attempt to capture the full age structure. Commonly used models of this type currently include, *inter alia*, TSA (Gudmundsson, 1994), SAM (Nielsen and Berg, 2014), SS3 (Methot and Wetzel, 2013), ASAP (Miller and Legault, 2015) and AAP (Aarts and Poos, 2009) where observations of the catch at age, and fishery independent data such as research vessel surveys, are used to reconstruct the historical population in the sea. Whereas TSA and AAP model discards explicitly, in some assessments the discard element is simply added to landings to obtain a total catch at age and much of the information about the discard process is lost. Discards may also be modelled as a separate "fleet" (e.g. NEFSC, 2013) where, although the integrity of discard observations is retained, there is an assumption that discards are generated as part of the capture process which is separate from the same fleet generating the landings. Since discarding is a post capture process it would be preferable to model discards as such in order both to preserve the behaviour of true fleets in the assessment and to provide information on the dynamics of discarding that may inform management.

Discarding occurs for a wide variety of reasons (Stratoudakis et al 1998; Catchpole et al 2006; Feekings et al 2012) and causes differ between stocks and fisheries. Here we consider discards that arise from target stocks that are subject to single species assessments rather than bycatch of unwanted species. In these stocks two common causes of discarding are that fish are below a marketable or legal minimum size, or that vessels are constrained by hold capacity or quota limits that prevent them from landing all the catch. We refer to these two elements as "size" or "bulk" discarding (Heath and Cook, 2015). A related intermediate process is "high grading" where quota or vessel capacity limits lead to only the more valuable size classes being retained even though smaller fish may be legally landed or have a market value (Batsleer et al, 2015).

The magnitude of different discard processes changes from year to year in response to market conditions and regulatory measures (Batsleer et al, 2015) and it is important to quantify them in order to understand and monitor the effects of management and to be able to calculate appropriate stock reference points. In many jurisdictions MSY is used as a framework to calculate management reference points which requires a definition of the catch to be maximised. In assessments of stocks in the Northeast Atlantic performed by the International Council for the Exploration of the Sea (ICES), for example, the catch to be maximised is defined as the landings and the fishing mortality associated with this component of the catch may be heavily influenced by the assumed pattern of discarding. It is common practice for these stocks to use the pattern averaged over a few recent years for the MSY calculation which, by implication, means that a fishery at MSY will continue to discard according to recent historical precedent. Where high grading or bulk discarding has occurred this may not be the appropriate assumption and needs to be accounted for in the estimation of the reference point.

In this paper we develop a model for discarding that can be incorporated into current catch at age stock assessment models to provide an historical perspective on patterns of discarding. The model distinguishes between size and bulk discarding so that transient effects can be identified and accounted for before MSY calculations are performed. The model is tested on simulated data and then applied to a number of stocks in the Northeast Atlantic that illustrate differing patterns of discarding.

Data

Eight stocks of demersal fish are considered which occur in the Greater North Sea (ICES Subarea 4 and Division 3a) and the West of Scotland (ICES Division 6a) and are listed in Table 1. Species considered were Cod (*Gadus Morhua,* Gadidae), haddock (*Melanogrammus aeglefinus,* Gadidae), whiting (*Merlangius merlangus,* Gadidae), saithe (*Pollachius virens,* Gadidae), plaice (*Pleuronectes platessa,* Pleuronectidae) and sole (*Solea solea*, Soleidae). These stocks are all subject to high rates of discarding (Catchpole et al 2005). They are assessed by ICES and the data used in this analysis were taken from the working group reports for these stocks (Table 1). The data comprise age compositions of landings and discards as well as age structured abundance indices from research vessel surveys. The same sources provide estimates of weight at age in the stock which are used here as a measure of size to inform the discard process.

The data used here are the same as used in the routine ICES assessments but subject to the following changes. The start year was chosen as 1983 since this is the year when one of the principal research vessel survey series is considered to have been standardised (the “IBTS”) and coincides with introduction of the Common Fisheries Policy in the European Union when discards became obligatory to comply with minimum landing sizes and quota limits on landings. However, some departure from this was necessary as for some stocks the discard data used in ICES assessments prior to 2002 are based on reconstructions rather than real observations. This applies to saithe and plaice. For these species only discard data from 2002 (saithe) and 2000 (plaice) onwards that are based on field observations were used. In the case of sole, no discard data are provided before 2002. Hence for these stocks the analysis is limited to the more recent period. This meant that some survey data covering earlier years used by ICES could not be included in the analysis.

For cod, haddock and whiting observations on discards prior to 2000 are based on the Scottish discard sampling programme that began in 1977. As Scottish vessels account for a high proportion of the catch of these stocks the discards for this fleet are considered representative for the whole fishery.

Methods

Discarding by fishing vessels is a post-capture process driven to a large degree by the length of fish. For the stocks considered, ICES reports generally do not report length but provide weight at age as a measure of size. In order to convert this to length, an inverse length-weight relationship was used to derive length from mean weight at age. For the gadoid species, relationships reported in Coull et al (1989) and for the flatfish from Robinson et al (2010) were used. Converting mean weight to length in this way will tend to give biased estimates of mean length where the amount of bias will depend of the distribution of length at age. It will be adequate, however, to provide a measure of size, albeit on an approximate scale.

In order to identify any relationship between discarding and size, the proportion discarded was estimated from the landings at age and discards at age for each year. These were then plotted against the estimated length at age for each year.

Discard model

Discarding is modelled as a post capture selection process. The principal equations for the model are set out in Table 2. The total number of fish discarded at each age is a time varying proportion of the total catch (equation T2.1). This proportion is age and year specific and is derived from a combination of size dependent and bulk discarding (equation T2.2) as described in Heath and Cook (2015) and Cook and Heath (2018). The size proportion is characterised by a conventional selectivity ogive based on a logistic function (Pope, 1975) where the 50% retention length, L50, is the location parameter and the selection range, SR, defines the slope (equation T2.3). Typically it might be expected that the 50% retention length would be close to the minimum landing size. However, if high grading occurs it might be expected to increase. Hence, the parameters of this function are allowed to vary over time so that discard selectivity can change (equations T2.4 and T2.5). The bulk proportion changes over time on the logit scale with normally distributed random errors (equation T2.6). This describes the response to quota or storage capacity limits that result in periodic discarding of all size classes of fish.

Assessment with Landings and Discards (ALD) model

It is straightforward to include the discard equations into any age structured stock assessment model. For convenience, here, the equations are incorporated into the model described in Cook (2019) and are set out in Table 3. The total mortality, Z, is split between fishing mortality, F, which is dynamic, and natural mortality, M, which is fixed. These mortalities reduce the number of the fish, N, at the start of the year according to equation T3.1. Total mortality is the sum of fishing mortality and natural mortality (T3.2). Fishing mortality is separable into an age effect and a year effect (T3.3) and these follow a random walk through time (T3.4 and T3.5) allowing selectivity to evolve.

For the stocks of whiting and haddock in the North Sea part of the catch is taken as bycatch in the industrial fisheries for fishmeal and fish oil. This component of the catch was modelled with a separate age and year effect equivalent to equations T3.3-T3.5 to allow for the different characteristics of the fleet which uses a smaller mesh and targets different species.

The observed quantities, catch and abundance indices, are given by the conventional Baranov catch equation and simple proportionality respectively (equations T3.6 and T3.7). For some stocks there is believed to be a problem of under-reporting the catches in a few years. To allow for this, equation T3.6 has an additional parameter to discount the observed catch. This problem only applies to the cod stocks in a few years as shown in Table 1.

Parameter estimation

Parameters were estimated by fitting the model to the data using Bayesian statistical inference with MCMC sampling in the R package “rstan” (Stan Development Team, 2016). For the landings, observation errors were assumed to be lognormal with age specific standard deviations (Table 4, equation T4.1). In the case of discards, the sampling level is generally very low leading to large observation errors. These were therefore assumed to have a negative binomial distribution parameterised in terms of a mean and dispersion (Crawley, 2013) to allow for over-dispersion (equation T4.2). The survey indices, as with the landings, were assumed to have age specific lognormal errors (equation T4.3). Observations that were zero were treated as missing values. For nearly all datasets very few zeros occurred.

Priors on the parameters were chosen to be uniform (Table 5). In the case of the initial populations and survey catchability these were on a log scale, and for the proportion bulk discarded this was on a logit scale. Three MCMC chains were run with a minimum of 300000 iterations, a burn in of 150000 and a thinning rate of 200. If the Rhat statistic was greater than 1 the iterations and burn in were doubled and the process repeated until convergence was achieved.

Model testing

The model was tested on simulated data to demonstrate that the parameters were estimable. Test data for a 35 year period were generated from a population resembling the cod stock in the west of Scotland. Landings, discards and two survey abundance indices were generated as pseudo data from the simulated population. The L50 was set at the minimum landing size (35cm) for the early years and then increased in more recent years. A similar pattern was applied to the selection range, SR. Two episodes of bulk discarding and three years of misreporting were included. The values of standard deviation for observation errors added to the landings, discard and survey data are shown in Table 6.

Thirty realisations of data were drawn from the true population. The assessment model was fitted to each if these in turn and the mean, maximum and minimum of the estimated values were then determined and compared to the true values.

Results

The relationship between the observed proportion of fish discarded and mean length at age is shown in Figure 1 where each age can be identified separately in the plot. With the exception of cod in 6a there is clear reduction in the proportion discarded as length increases, as would be expected. Within age groups there is also a trend for fish with a smaller mean length to have higher discard rates. For the age groups that span the 50% retention length, the range in proportion discarded can be very large so that in sole, for example, the proportion of 1 year old fish discarded can be as low as 25% but as high as 100%. A similar effect can be seen for 3 year old fish in whiting in 4,7d, plaice and saithe, and 2 year olds in haddock. Although most stocks show declining proportions discarded with length, the scatter around this trend is very large for cod in 6a and is also apparent in North Sea cod, the whiting stocks and plaice. This is due to high grading and bulk discarding in some years.

The model recovered the true values from the simulated data (Figure 2) showing that the parameters of the discard model were estimable. There is little sign of systematic bias.

The change in the 50% retention length for the eight demersal stocks is shown in Figure 3. For the cod and whiting stocks there is an increase in retention length which begins in the early years of this century. The change is most marked in cod with the increase occurring from 2006 and plateauing after 2010. The west of Scotland cod has the largest change with an increase from 35cm to nearly 70cm. The change in the west of Scotland whiting is fairly continuous while in the North Sea whiting it is much more variable. Of the remaining stocks only plaice shows a persistent downward trend while the others show little net change.

The selection range, which is a measure of the slope of the retention curve, shows some similarity to the L50 trend for the cod stocks (Figure 4) with an increase occurring at a similar time. For the other stocks there is much more variability but with an increase in the case of sole and perhaps saithe.

The estimates of bulk discarding show that it is rare but can occasionally be large (Figure 5). The greatest effect is seen for west of Scotland cod where nearly 40% of the catch may be discarded in bulk in some years. North Sea cod shows some bulk discarding but this is only around 10%. For plaice there appears to be more frequent bulk discarding in the years available but is typically fairy low except for a few years when it approaches 20-30%.

The need to account for both size related and bulk discarding is summarised in Figure 6 which compares the predicted proportion discarded to the observed proportion. As expected the fitted proportions (solid dots) lie around the one-to-one line, though there is an indication of systematic lack of fit in the case of sole. The proportion discarded due only to size is shown as open circles and it can be seen that for cod, whiting and plaice these often lie well below the one-to-one line as the result of high bulk discarding in some years. More detailed model fits to the discard data are given in Supplementary Information (Figures s1-s8).

Table 1 shows the estimated clumping parameter of the negative binomial distribution for the discard data. The values for cod and whiting are largest and hence indicate lower dispersion than other stocks. This may, in part, be due to differences in the way discards are sampled for the different stocks and is discussed below.

Except for the west of Scotland cod, the assessment model produces similar trends in mean fishing mortality and spawning stock biomass (SSB) as the standard ICES assessments (Figures 7 and 8) though there are differences in scale. This is a common phenomenon when different assessment models are applied to the same data (Deroba et al 2015). The assessment model tended to estimate lower fishing mortality and higher SSB than the equivalent ICES assessment. To some extent these difference in scale can be attributed to shorter time series of data being used. When a longer time series of data were used for saithe, plaice and sole, the estimated SSB is much closer to the ICES assessment (Supplementary Information, Figure s9-s10). However, these longer time series were not used due to the absence of real discard data in the early years. In the case of west of Scotland cod, the assessment differs substantially from the ICES and appears to be the result of the estimated fishery exploitation pattern. In the ICES assessment the exploitation pattern is assumed to be flat-topped whereas ALD does not constrain the shape. When the ALD model was constrained in the same way it gave very similar results to the ICES assessment but is not consistent with effort data (Cook, 2019) and this configuration was not therefore used.

Discussion

Examination of the raw data shows that discarding in the stocks analysed is related primarily to size Figure 1). Although age is a proxy for size, variation in growth means that using age as an explanatory variate in modelling the proportion discarded may not adequately capture changes in discard rates. In some stock assessments discard estimates are reconstructed assuming that a constant proportion of fish at each age are discarded. In the saithe stock for example, ICES made this assumption for data prior to 2002 in the 2018 assessment (ICES 2018c) yet it is clear from Figure 1 that three year old fish are subject to high variation in the proportion discarded and this is dependent on mean length at age. A more realistic reconstruction could therefore be achieved by accounting for size. In the case of the cod and whiting stocks (and to some degree plaice) size alone is not an adequate predictor of the proportion discarded and changes in size selection and the transient effects of bulk discarding need to be considered.

Tests on simulated data show that the model can recover true values, though this is conditioned on these data conforming to the same assumptions as in the model. When applied to real data from eight demersal stocks with differing biology, the model estimates similar trends in SSB and mean fishing mortality as estimated by ICES. The latter are derived from a range different assessment models (Table 1) and taken together suggest the model developed here can provide an equivalent perception of stock trends while including more explicit information on discards.

Results for cod and whiting indicate that both the 50% retention length and selection range have increased. This is indicative of a shift to larger fish being discarded and is consistent with high grading which occurs when market conditions or regulatory measures incentivise the retention of only the most valuable sizes of fish (Gillis et al 1995, Depstele, et al, 2011, Kraak et al, 2013). Both the cod stocks have been the subject of recovery plans (EU 2008) following years of decline and these have included restrictive quotas. Scientific advice from 2000 onwards was for zero catches for both stocks though TACs were usually set to allow a fishery (ICES 2018a, b) to operate while attempting to constrain fishing mortality. Restrictive quotas initially had little effect on reducing fishing mortality and large quantities of fish were landed illegally. ICES working group estimates of unreported catch were as high as 60% in some years (ICES 2018c, d). Legislative measures introduced by the UK in 2005 (Scottish Statutory Instruments ,2005) that required fish to be landed at designated ports and handled by registered buyers and sellers improved traceability and meant that illegal landings were much reduced. However, this resulted in large quantities of fish being discarded in order for vessels to comply with quota limits which at that time applied only to landings. The effect is most obvious in the west of Scotland cod where quantities of discards increased from around 7% of the catch in 2005 to 48% in 2006 (ICES 20018d). The effect in the

North Sea is less dramatic but discards increased from 28% in 2005 to 55% in 2007 (ICES 2018c). This period also coincides with the occurrence of bulk discarding where much of the catch is simply dumped to comply with landing restrictions.

While the magnitude of the high grading effect is less in the whiting stocks, there has nevertheless been an increase in the 50% retention length and, arguably, the selection range. These stocks have also shown chronic declines and were subject to restrictive quotas that are likely to have contributed to the higher rates of discarding of larger fish.

Although there is a small decline in the 50% retention length for plaice, the most notable effect is the apparent occurrence of bulk discarding between 2007 and 2009. These estimates arise due to the high numbers of fish appearing in some, but not all, older age groups in the discard data. Thus while there is a signal for bulk discarding is it not consistent across age groups (Supplementary Information, Figure s9). The data are very noisy and the clumping parameter is low (Table 1) indicating very high dispersion. Discard estimates for this period are partly dependent on self-sampling schemes and this may affect data quality , but it may simply be a reflection of small sample size. In the absence of a clear causal mechanism of these discard rates, they should be treated with caution.

Unlike the flatfish stocks, cod, haddock and whiting discards data are derived mainly from at-sea sampling by scientific observers. The cod and whiting discard data show lower dispersion with higher values of the clumping parameter (Table 1) and this may be due to a sampling design where balance and quality control are more readily applied. Such sampling schemes are not without problems (Stratoudakis et al, 1999; Benoît and Allard, 2008; Rochet and Trenkel, 2005) and bias may still occur.

There are, perhaps, two important issues that arise from the inclusion of discard data in stock assessments. One relates to the correct weighting of data in the in the assessment model, and the other to the interpretation of selectivity in forecasts and equilibrium calculations. Typically discard data are subject to higher sampling error than landings and this needs to be accounted for when fitting models (Francis, 2011). Dickey-Collas et al (2007), for example point out that reduction in bias through the inclusion of discards in an assessment can be outweighed by a decrease in precision. Their analysis was based on XSA (Shepherd 1999) where the model is applied to combined landings and discards at age. In this case, provided the pattern of discarding is consistent across years, errors in the data are likely to be similar over time. In the examples considered in this paper it is clear that for some stocks the pattern of discarding changes through time and the proportion of the catch comprising discards increases. It means that errors in the combined catch at age matrix are not time invariant as is assumed in some stock assessments (e.g. North Sea cod) and in more recent years will tend to over-weight the catch data relative to the surveys. It points to the need to model discards separately as is done in TSA (Fryer, 2002; Needle and Fryer, 2002) and AAP (Arts and Poos, 2009). These models treat discard selectivity as a random effect that evolves over time and has the advantage of flexibility that can accommodate changing patterns of discarding while more appropriately weighting the observations relative to other data in the assessment. In effect a time series model is used to smooth the estimates. However, the approach is non-parametric and the models do not explicitly characterise the discard process that give rise to the observed quantities. The parametric model described here offers a means of identifying changes in fleet behaviour that can be used for management purposes, such as the change in the retention length.

In some modelling frameworks, such as ASAP (Miller and Legault, 2015) discards may be explicitly modelled as separate fleets (e.g. NEFSC 2013). Here the catch from a group of vessels is split into two fleets, one accounting for landings, the other discards. This overcomes the issue of the error distribution in the observations but at the cost of interpreting model parameters. In this case estimated fleet selectivity is a compound of the selectivity at the point of capture and the post-harvest selection of fish to discard. Where the fleet partial fishing mortality is modelled as an age and year effect analogous to equation T3.3, and the year effect is fleet specific, it may be problematic to interpret the parameters. For a “true” fleet the year effect represents an overall scaling value on the selection pattern but where landings and discards have individual year effects, they are inextricably linked to the fleet selection patterns which themselves are the product of true fleet selectivity and discarding choices.

In ALD the discard process is modelled as a post-capture process that may have advantages in interpreting selectivity and patterns of discarding. Here, true fleet selectivity is preserved and discarding is characterised parametrically so that when investigating alternative future management scenarios a clear distinction is made between the processes where management effort may be directed.

In age structured assessments forecasts of stock development and potential catches are based on the recent exploitation pattern in the fishery and this is frequently a mean value taken over a period of recent years. There is an implicit assumption that what happens in the near future is related to the recent past. As a point of departure this is reasonable but as can be seen for cod, patterns of discarding may be transient and heavily influenced by annual management constraints. The ALD model can be used to identify the transient effects of bulk discarding which can then be removed from forecasts where appropriate. In addition, if high grading is unlikely to be propagated into the future, the 50% retention length can be adjusted to account for this. Since the model is predicated on mean length at age, it is also possible to use the growth of specific cohorts to obtain a more precise estimate of the proportions of fish that are subject to discarding than an historical average.

The pattern of discarding is also relevant to the calculation of reference points such as those based on MSY. Estimates of F_{MSY} are conditioned on the choice of which catch component to maximise. For the stocks presented here it is the landings that are maximised in the calculation of F_{MSY} and these will be affected by the assumed discarding pattern. Typically F_{MSY} is lower when the landings, as opposed to the total catch, are maximised. In this context, ICES defines *“yield to be catch above the minimum catch/conservation size. When the selection pattern corresponding to this cannot be estimated, ICES uses the recent landings selection to define yield.”* (ICES 2018e). Since size is generally absent from the age structured models in these assessments, it is the landings that are often used to derive an exploitation pattern. It can mean that there is an implicit assumption of large quantities of fish above the minimum catch/conservation size being discarded because discard dynamics are not available from the assessment. The estimation of F_{MSY} for North Sea cod, for example, used an average exploitation pattern from recent years (ICES 2014) which will include the effects of both bulk discarding and high grading (Figures 3 and 5), both phenomena which are less likely to occur in a fishery operating at an MSY equilibrium. It demonstrates the need to account for discarding more realistically when evaluating reference points.

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Data Availability Statement

The data used in the analysis are available in the ICES stock assessment working group reports referred to in the main text and can be accessed at http://www.ices.dk/

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Table 1. Summary of stocks used in the analysis. ICES area definitions are; Kattegat and Skagerrak (3a), Skagerrak(Subdivision 20), North Sea (4), West of Scotland (6a), Rockall (6b),Eastern Channel (7d). Details of the surveys and their acronyms are given in the respective working group reports. The clumping parameter (dispersion) κ, estimated from the model is a measure of overdispersion for the discard data. Lower values of κ indicate higher dispersion.

Stock	**ICES stock area**	**Years used for landings and discards**	**Surveys**	**ICES Assessment model**	**Years for under-reporting**	**κ**	**ICES working group source**
Cod, West of Scotland	6a	1983-2017	ScoGFS-WIBTS Q1 UK-SCOWCGFS-Q1 ScoGFS-WIBTS-Q4 UK-SCOWCGFS-Q4 IRGFS-WIBTS-Q4	TSA (Needle and Fryer, 2002)	1993-2007	2.96	ICES 2018d
Cod, North Sea,	4,7d, Subdivision 20	1983-2017	IBTS Q1 IBTS Q3	SAM (Nielsen and Berg, 2014)	1993-2005	3.23	ICES 2018c
Whiting, West of Scotland	6a	1983-2017	ScoGFS-WIBTS Q1 UK-SCOWCGFS-Q1 ScoGFS-WIBTS-Q4 UK-SCOWCGFS-Q4 IRGFS-WIBTS-Q4	TSA (Needle and Fryer, 2002)	N/A	2.07	ICES 2018d
Whiting, North Sea	4,7d	1983-2017	IBTS Q1 IBTS Q3	SAM (Nielsen and Berg, 2014)	N/A	3.33	ICES 2018c
Haddock, Northern shelf	4,6a	1983-2017	IBTS Q1 IBTS Q3	TSA (Needle and Fryer, 2002)	N/A	1.64	ICES 2018c
Saithe, North Sea, West of Scotland	3a,4,6a,6b	2002-2017	IBTS Q3	SAM (Nielsen and Berg, 2014)	N/A	1.46	ICES 2018c
Plaice, North Sea	4,Subdivision 20	2000-2017	IBTS Q1 SNS2 BTS combined	AAP (Aarts and Poos, 2009)	N/A	1.51	ICES 2018c
Sole, North Sea	4	2002-2017	BTS-ISIS SNS	AAP (Aarts and Poos, 2009)	N/A	1.76	ICES 2018c

Table 2 Equations specifying the discard model.

No.	Equation	Comment
T2.1	$D_{a,y} = pd_{a,y}C_{a,y}$	Discarded number, *D*, is a proportion, *pd*, of the total catch at age, C, where *a* and *y* denote age and year
T2.2	$pd_{a,y} = ps_{a,y} + pq_y - pq_y ps_{a,y}$	The total proportion discarded is a function of the proportion discarded by size, *ps*, and the proportion discarded in bulk, *pq*.
T2.3	$ps_{a,y} = 1 - \frac{1}{1 + \exp\left(\frac{\ln(9)\left(L50_y - l_{a,y}\right)}{SR_y}\right)}$	The size proportion is given by a logistic selection ogive defined by the 50% retention length, L50, and the selection range, SR. The variable $l_{a,y}$ is the mean length at age *a* in year *y*.
T2.4	$L50_y = L50_{\mathrm{y}-1} + \epsilon_y^{L50}$	The L50 follows a random walk through time with a normal error ϵ_y^{L50} .
T2.5	$SR_y = SR_{\mathrm{y}-1} + \epsilon_y^{SR}$	The selection range follows a random walk with a normal error ϵ_y^{SR}
T2.6	$logit(pq_y) = logit(pq_{\mathrm{y}-1}) + \epsilon_y^{pq}$	The proportion of fish discarded in bulk follows a random walk on the logit scale with normal error ϵ_y^{pq}

Table 3. Population model equations

No.	Equation	Comment
T3.1	$N_{a,y} = N_{a-1,y-1}e^{-Z_{a-1,y-1}}$	The population N at age a and year y decays exponentially with total mortality Z.
T3.2	$Z_{a,y} = M_a + F_{a,y}$	The total mortality Z is partitioned between natural mortality M, and fishing mortality F.
T3.3	$F_{a,y} = s_{a,y}f_y$	Fishing mortality is separable into an age effect, s, and year effect, f. Selectivity, s, is set to 1 for a reference age in all years for identifiability.
T3.4	$f_y = f_{y-1}\epsilon_y^f$	Annual fishing mortality follows a random walk with lognormal process error
T3.5	$s_{a,y} = s_{a,y-1}\epsilon_{a,y}^s$	Selectivity follows a random walk with lognormal process error
T3.6	$C_{a,y} = p_y \frac{F_{a,y}}{Z_{a,y}} N_{a,y}(1 - e^{-Z_{a,y}})$	The observed catch, C, is calculated using the Baranov equation. The parameter p_y is a reporting factor to account for under-reported catch.
T3.7	$u_{a,y,k} = q_{a,k}N_{a,y}e^{-\pi_k Z_{a,y}}$	The survey indices are proportional to the population, where k indexes survey and π is the proportion of total mortality occurring before the survey takes place.

Table 4. Observation error distributions.

No.	Equation	Comment
T4.1	$L'_{a,y} \sim lognormal(\log(L_{a,y}), \sigma^L_a)$	The landings,*L*, are observed with lognormal error, σ^L .
T4.2	$D'_{a,y} \sim negative\ binomial(D_{a,y}, \kappa)$	The discards,*D*, are observed with negative binomial error, with a clumping (dispersion) parameter,κ .
T4.3	$u'_{a,y,k} \sim lognormal(\log(u_{a,y,k}), \sigma^I_{a,k})$	Survey indices are observed with lognormal error σ^I

Table 5. Prior distributions on the parameters.

No.	Equation	Comment
T5.1	$log(N_{1,y}) \sim uniform(3,20)$ $\log(N_{a,1}) \sim uniform(3,20)$	Initial populations are drawn from log uniform distributions
T5.2	$f_1 \sim uniform(0,2)$ $\sigma^f \sim uniform(0,1)$	Initial fishing mortality and the standard deviation of the process error on f are drawn from uniform distributions
T5.3	$\mathrm{s}_{\mathrm{a},1} \sim \mathrm{uniform}(0,2)$ $\sigma^s \sim \mathrm{uniform}(0,1)$	Initial selectivity at age and the standard deviation of the process error on s are drawn from uniform distributions
T5.4	$\log(\mathrm{q}_{\mathrm{a,k}}) \sim \mathrm{uniform}(-20,0)$	Log survey catchability is drawn from a uniform distribution
T5.5	σ_a^L~uniform(0,2)	Measurement error on the landings is drawn from a uniform distribution
T5.6	κ~uniform(0,1000)	The clumping or dispersion parameter of the negative binomial distribution for discards is drawn from a uniform distribution
T5.7	$\sigma_{a,k}^I$~uniform(0,2)	Measurement errors for the survey indices are drawn from a uniform distribution.
T5.8	$\mathrm{p}_y \sim \mathrm{uniform}(0,1)$	The proportion of the catch reported is drawn from a uniform distribution.
T5.9	$L50_1$~uniform(20,50) σ_y^{L50}~uniform(0,10)	Initial 50% retention length and the standard deviation of the process error are drawn from uniform distributions
T5.10	SR_1~uniform(1,15) σ_y^{SR}~uniform(0,10)	Initial selection range and the standard deviation of the process error are drawn from uniform distributions
T5.11	Logit(pq_1)~uniform(-50,50) σ_y^{pq}~uniform(0,10)	Initial bulk discarding proportion is drawn from a uniform distribution on a logit scale. The standard deviation of the process error is drawn from a uniform distribution

Table 6. Standard deviations of measurement error distributions used in the simulated data. For discard data the clumping parameter was set at 2.

Age	Landings	Survey 1	Survey 2
1	0.600	0.560	1.000
2	0.142	0.137	0.381
3	0.092	0.120	0.261
4	0.094	0.177	0.234
5	0.115	0.314	0.238
6	0.150	0.572	0.255
7	0.197	1.000	0.279

Figure legends

Figure 1. Observed proportion discarded at each age as a function of mean length at age for eight demersal fish stocks for the period of years listed in Table 1. Each age is plotted with a different symbol to show that proportions may vary by size within age groups. Each point is related to an individual year.

Figure 2. Model fit to simulated data. Solid line shows the mean of 30 model fits. Grey area shows the maximum and minimum values. Dots show the true values.

Figure 3. 50% retention length, L50, for eight stocks of demersal fish. Shaded area is the 95% credible interval and the solid line the median. Dotted lines show the minimum landing sizes in effect during the period and which are now defined as the “minimum conservation reference size”. Note that differences in scale on the Y axis mean that comparisons across stocks should be treated with caution.

Figure 4. Selection range, SR, for eight stocks of demersal fish. Shaded area is the 95% credible interval and the solid line the median.

Figure 5. Proportion of catch discarded in bulk for eight stocks of demersal fish. Shaded area is the 95% credible interval and the solid line the median.

Figure 6. Proportion of the catch discarded for eight stocks of demersal fish for the years listed in Table 1. Solid dots show the total proportion discarded and the open circles the proportion due to size only. The solid line of slope 1 shows the one-to-one relationship. Each point relates to an individual year.

Figure 7. Mean annual fishing mortality for eight stocks of demersal fish. The solid line shows median estimated value and the shaded area the 95% credible interval. The dots show the values from the ICES assessments. Equivalent plots for the full time series for saithe, plaice and sole using derived discard data in earlier years are shown in Supplementary Information Figure s9.

Figure 8. Spawning stock biomass (SSB, in tonnes) for eight stocks of demersal fish. The solid line shows median estimated value and the shaded area the 95% credible interval. The dots show the values from the ICES assessments. Equivalent plots for the full time series for saithe, plaice and sole using derived discard data in earlier years are shown in Supplementary Information Figure s10.