ICES Journal of Marine Science (2011), 68(8), 1719–1725. doi:10.1093/icesjms/fsr030

Quantifying causes of discard variability: an indispensable assistance to discard estimation and a paramount need for policy measures

Jochen Depestele[1,2]*, Sofie Vandemaele[1,3], Willy Vanhee[1], Hans Polet[1], Els Torreele[1], Herwig Leirs[3], and Magda Vincx[2]

[1]The Institute for Agricultural and Fisheries Research (ILVO), Ankerstraat 1, B-8400 Ostend, Belgium
[2]Ghent University, Marine Biology, Krijgslaan 281-S8, B-9000 Ghent, Belgium
[3]University of Antwerp, Groenenborgerlaan 171, B-2020 Antwerp, Belgium

*Corresponding Author: tel: +32 59569838; e-mail: jochen.depestele@ilvo.vlaanderen.be.

Depestele, J., Vandemaele, S., Vanhee, W., Polet, H., Torreele, E., Leirs, H., and Vincx, M. 2011. Quantifying causes of discard variability: an indispensable assistance to discard estimation and a paramount need for policy measures. – ICES Journal of Marine Science, 68: 1719–1725.

Received 28 September 2010; accepted 6 February 2011; advance access publication 29 March 2011.

Fishery-dependent data underpin the scientific advice given to fishery managers. However, discard estimates are often imprecise as a result of limited sampling coverage. Estimating discard rates from length frequency distributions (LFDs) in commercial catches may complement information from observer trips. The accuracy of estimates depends greatly on careful investigation of the discard variability. Here, the impact of three essential factors was quantified for beam-trawl fisheries in the southern North Sea: (i) market prices, (ii) landings per trip (LPT) limitations, and (iii) selectivity of the commercial fishing gear. Observed discard rates for cod, plaice, sole, and whiting were compared with estimates based on length frequency data, taking account of the variability attributable to LPT limitations and market price. Observed discard estimates of cod and whiting differed significantly from LFD-derived estimates because of highgrading. The results indicate that LFD-derived discard estimates are only reliable if the crucial driving factors are quantified. LFDs can be collected from research vessels or by fishers in partnership with scientists. Based upon many of these LFDs and the discard-variability factors identified in observer programmes, discard rates can be estimated better.

Keywords: beam trawl, discards, fishery management, highgrading, market price, minimum landing size, North Sea, quota.

Introduction

North Sea fisheries are responsible for the highest level of discards in the world (Kelleher, 2005), although discard rates have dropped in recent years (Aarts and Poos, 2009; Enever *et al.*, 2009). Fishery management is expected to reduce fisheries discards (Enever *et al.*, 2009), especially discards of the beam-trawl flatfish fishery in the North Sea (Catchpole *et al.*, 2008). This fishery is among the greatest generators of discards in the North Sea (Catchpole *et al.*, 2005).

Reliable estimates of discard rates and the causes of their variability are of paramount importance both for stock assessment (Dickey-Collas *et al.*, 2007) and effective fishery management (Rochet and Trenkel, 2005). Currently, estimates of discards are highly imprecise, owing to the limited coverage of the fleet for discard sampling (Dickey-Collas *et al.*, 2007).

Estimating discard rates from gear selectivity characteristics, in addition to observer data, may provide valuable information for commercial fish species. Several exercises illustrate this theory, e.g. for discards of non-commercial fish species (Piet *et al.*, 2009), for historical discards (Aarts and Poos, 2009), and for studying spatio-temporal variation in discarding (Welch *et al.*, 2008). Discard rates can be inferred from the assumption that commercial fish below minimum landing size (MLS) are discarded, whereas those above MLS are landed. The discarding of marketable fish, defined as highgrading (Gillis *et al.*, 1995a), can reduce the accuracy of such discard estimates (Piet *et al.*, 2009). Length frequency distributions (LFDs) associated with each type of commercial fishing gear can be obtained from gear-technology trials or directly from fishers. Additionally, they can be deduced from selectivity parameters and estimates of absolute abundance. The latter are obtained by raising fish-density data while taking account of the catchability of survey gear (Piet *et al.*, 2009). Adding this method of discard estimation to current monitoring programmes could expand the number of records and has the potential to extend the spatio-temporal distribution of discard data at low cost (Polet *et al.*, 2010).

Discard estimates from modelling exercises depend on fish abundance, fishing effort, MLS, and gear selectivity (Piet *et al.*, 2009). Market incentives and policy measures have been identified as crucial drivers of discarding, but there seems to be no quantitative assessment of their contribution to the discarding problem (Rochet and Trenkel, 2005).

Here we elucidate the market- and policy-driven causes of discarding. To illustrate it, four commercial fish species were selected from the Belgian flatfish beam-trawl fishery in the southern North Sea, Dover sole (*Solea solea*), plaice (*Pleuronectes platessa*), cod

(*Gadus morhua*), and whiting (*Merlangius merlangus*). Understanding the reasons for discarding may have implications for policy measures such as quota restrictions and gear regulations. It also clarifies what parameters other than gear selectivity and MLS need to be taken into account when estimating discards of commercial fish species.

Material and methods

The Belgian discard-sampling programme

The study focused exclusively on the Belgian flatfish-directed beam-trawl fishery in the southern North Sea (ICES Division IVc) during 2006, 2007, and 2008. Fishery-dependent data are collected for the Belgian beam-trawl fleet in accordance with the EC Data Collection Regulation (EC, 2000). These include landing and discard data from commercial vessels, obtained since 2004 through on-board observation. Selection of the vessels for this observer programme is random but conditional on the cooperation of fishers. The data were collected during fishing activities in one or more ICES Divisions, e.g. IVb and IVc. Fishing trips were defined as the primary sampling units, and hauls within a fishing trip as secondary sampling units. The latter are correlated within trips, implying that hauls are not independent and can confound statistical analyses (see below). The sampled gear was a beam trawl, 4 or 12 m wide, equipped with a chain mat and a codend of 80 mm mesh.

Sampling coverage ranged between 2.4 and 4.5% of landings, comparable with other discard-sampling programmes (e.g. Stratoudakis *et al.*, 1998; Rochet *et al.*, 2002). The spatial distribution of sampling is a good reflection of commercial fishing activity in the southern North Sea (Figure 1), which was primarily in the west of the area. In all, 28 trips (374 tows) were sampled on board nine beam trawlers. Every alternate haul was sampled by the observers, unless that haul was rejected (e.g. as a result of severe net damage, <3%), in which case the next haul was sampled. Sampling took place around the clock to reflect typical working conditions. Fishers sorted the marketable fish from the conveyor, and the observers also collected all commercial fish species discarded, both undersized and highgraded. The observers did not interfere with fishing operations. However, an observer effect resulting from changes in fishing practice and location could bias the observed discard rates (Liggins *et al.*, 1997; Benoît and Allard, 2009).

Discard rates and highgrading

Marketable and discarded fish samples were weighed and fish lengths measured to the nearest centimetre below. In 68% of the hauls, the lengths of all fish were measured. Only when an observer judged the abundance of a species to be excessive was a subsample taken of at least one 40-l basket. To ensure that sufficient fish of each size category were sampled, observers identified the most obvious length modes (Cotter and Pilling, 2007). The total number of discards by length per species in the relevant haul was estimated using the subsampling fraction and the observed length distribution. The mean of the subsampling factors was 1.54, with a minimum of 1.0 and a maximum of 10.8. LFDs were determined for sole, plaice, cod, and whiting. Sole and plaice constituted most of the landings, about 20% each, in contrast to cod and whiting which were considered bycatch (7 and ~1%). In this context, bycatch is defined as commercial species not targeted but nevertheless in the landings. Discard rates, in

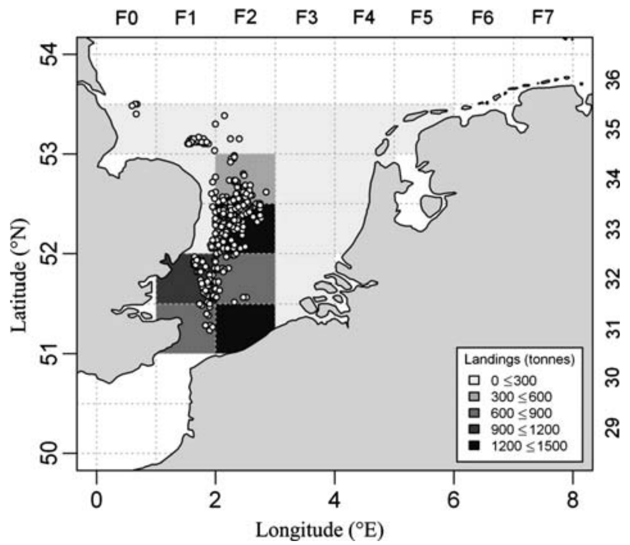

Figure 1. Spatial distribution of the total landings of sole, plaice, cod, and whiting by Belgian flatfish beam trawlers in the southern North Sea (shaded areas) and sampled hauls (open circles).

both number and weight, were estimated directly from at-sea observations (D_{obs}) and also calculated from LFDs of the catch and MLS (D_{estim}). The discard rate (D) was defined according to Rochet and Trenkel (2005):

$$D\ (\%) = \frac{d}{d+k} \times 100, \quad (1)$$

where d is the weight or numbers of the discarded fish (caught but not kept) and k the ungutted weight or numbers of the harvested fish (caught and retained). D_{obs} therefore includes possible highgrading, because the discarded (d) and harvested (k) fractions depend on the sorting behaviour of fishers. The ungutted weight of harvested fish, needed to calculate D_{obs}, was obtained using gutting factors of 1.04 for sole, 1.05 for plaice, 1.18 for whiting, and 1.17 for cod (EC, 2009).

Calculating discard rates based on LFDs and MLS (D_{estim}) partly reflects the selectivity of the beam trawl and does not account for the sorting behaviour of fishers. Fish below MLS were considered discards (d), whereas those above MLS were assumed to be harvested (k). Consequently, highgrading was not considered in D_{estim}. Equation (1) gives D_{estim} in numbers, and a length–weight conversion is needed to obtain the corresponding weight. Relevant data were collected in the southern North Sea during August and September of 2007 and 2008, during research surveys with the RV "Belgica". The total length of the fish (L, cm) was measured to the nearest 0.5 cm below, and ungutted wet weights (wt, g) were also recorded at sea. Numbers were converted to length using a weight–length relationship (Table 1).

Factors affecting the highgrading of cod and whiting

Discard rates estimated directly from LFDs were compared with on-board observations using t-tests. Any discrepancies between the observed and estimated discard rates may be related to market price, landings per trip (LPT) limitations, and/or catch composition. These factors were evaluated as explanatory factors for discarding fish above MLS. Mean fish prices were retrieved

Table 1. Parameters of the length–weight relationship for sole, plaice, cod, and whiting in the southern North Sea during August and September of 2007 and 2008.

Species	*a*	*b*	Pearson r^2	*n*	Minimum (cm)	Maximum (cm)
Sole	0.007568	3.0617	0.9862	2 724	5.5	40.5
Plaice	0.009641	3.0319	0.9935	2 897	8.5	57
Cod	0.010137	2.9912	0.9904	83	15.5	62
Whiting	0.009030	2.9508	0.9898	1 021	5.5	39

from the fishing ports of Ostend, Zeebrügge, and Nieuwpoort. The LPT constraints for each sampled vessel were calculated from national regulations, which specify the maximum allowable LPT-day based on engine power. The maximum allowable landings varied over time, according to national management decisions, ensuring that the total landings of the Belgian fleet matched national quota restrictions. The maximum allowable landings of whiting were 250 kg d^{-1} for Belgian beam trawlers in 2006, but no limitations were set in 2007 and 2008. On 27 November 2008, the fishery for whiting was closed. Constraints on catch composition are set by EU regulation. The catch must consist of at least 70% of listed species at all times before return to port (EC, 1998). The list includes a wide range of species, including, for instance, sole, plaice, dab (*Limanda limanda*), brill (*Scophthalmus rhombus*), and turbot (*Psetta maxima*). Cod is not in the list, but whiting is. To investigate the influence of catch composition, whiting was considered at risk of being discarded if the composition of trip landings had >75% of listed species. Similarly, cod could not exceed 20% of the landings. This factor was included in the analysis by considering cod discards to be likely if a trip landing of cod exceeded 15%.

Statistical analysis

A response variable R was created to model the discrepancy for discard rates by weight:

$$R = \frac{D_{obs}}{D_{obs} + D_{estim}}, \quad (2)$$

where D_{obs} is the observed discard rate and D_{estim} the discard rate estimated from LFDs and MLS. LPT, fish price, and catch composition were *a priori* selected to explain the discrepancy. For whiting, the effect on the response variable was tested using a multivariate generalized linear mixed effect model (GLMM) with Gaussian distribution. Fixed effects were fish price, nominal LPT, their interaction, and the risk of exceeding the landings composition with listed species >75% as another factor. Fishing trips were included as a random, nesting factor to account for inter-haul correlations. Model selection was carried out using stepwise backward selection with the Akaike information criterion (AIC) as the selection criterion. A similar approach was followed for modelling the highgrading of cod, i.e. before the MLS was shifted from 40 to 50 cm by national legislation (MB 14 December 2007). A GLMM was fitted to account for the random variability induced by fishing trip, and LPT was included as a continuous variable. The homoscedasticity and normality assumptions were verified through visual analysis of the residuals (not shown). However, the response variable could not theoretically have values >1 or <0.5 because D_{obs} cannot take values smaller than D_{estim}. Therefore, a generalized additive mixed model (GAMM) was fitted. A two-dimensional tensor-product of cubic regression splines for LPT and fish price was used in the full model (Wood, 2006). The final model of backward selection was refitted with one-dimensional cubic regression splines and restricted maximum likelihood (REML; Zuur *et al.*, 2009).

Table 2. Mean discard rates and standard deviations (s.d.) for sole, plaice, cod, and whiting in Belgian beam-trawl fisheries in the southern North Sea during 2006, 2007, and 2008.

Species	Observed discard rate mean (s.d.)	Estimated discard rate mean (s.d.)	Difference observed and estimated discard rate mean (s.d.)
Sole	0.29 (0.18)	0.25 (0.16)	0.04 (0.04)
	0.13 (0.11)	0.11 (0.10)	0.02 (0.03)
Plaice	0.42 (0.24)	0.39 (0.22)	0.02 (0.07)
	0.27 (0.21)	0.25 (0.18)	0.03 (0.10)
Cod	0.65 (0.29)	0.55 (0.31)	0.10 (0.27)
	0.47 (0.31)	0.36 (0.31)	0.12 (0.24)
Whiting	0.70 (0.33)	0.55 (0.29)	0.15 (0.51)
	0.61 (0.33)	0.46 (0.27)	0.15 (0.16)

Upper rows, number-based discard rates; lower rows, weight-based rates. The observed rates have been determined at sea, whereas the estimates are obtained from LFDs of landings and MLSs. Their differences indicate the validity of using LFDs and MLSs for discard estimation.

Results

Discard rates and highgrading

To estimate the discard rates by weight, numbers-at-length were converted to weight-at-length, using length–weight relationships. Parameters a and b of the length–weight relationships are given in Table 1, together with the regression coefficient (Pearson r^2), the number of individuals measured (n), and the sizes of the smallest and largest fish measured.

Discard rates are presented as numbers and weights for sole, plaice, cod, and whiting (Table 2). The observed and the estimated discard rates differed significantly ($p < 0.01$ in a paired t-test) for all four species. Examining LFDs shows that the discard rates were apparently dictated by MLS for sole and plaice, but less so for whiting and cod, of which there was substantial discarding above MLS (Figure 2). This is equally demonstrated by the higher standard deviations of the differences between the observed and estimated discard rates for cod and to some degree for whiting. The LFD curves for cod and whiting imply that factors other than MLS determine discarding. The mean proportion of discarded fish above MLS was calculated for each quarter in each sampling year (Table 3). Few cod were apparently highgraded in 2006, but in the final quarter of 2007 and the first and second quarters of 2008, highgrading was recorded. Whiting was highgraded in each quarter in each year, although highgraded proportions were less in the second quarter of 2006 and the first of 2007. Highgraded proportions of whiting were higher in the fourth quarter of 2006 and the second quarter of 2008; no data were available for the first quarter of 2007. The findings suggest that discards of fish above MLS did not change predictably between years. Factors driving highgrading of cod and whiting were then investigated in more detail.

Factors affecting the highgrading of cod and whiting

The LPT limitation for cod varied over the year, without any obvious, repeated pattern (Figure 3). Fish prices were also variable: €2.9–4.5 per kg for cod and €1.0–2.4 per kg for whiting

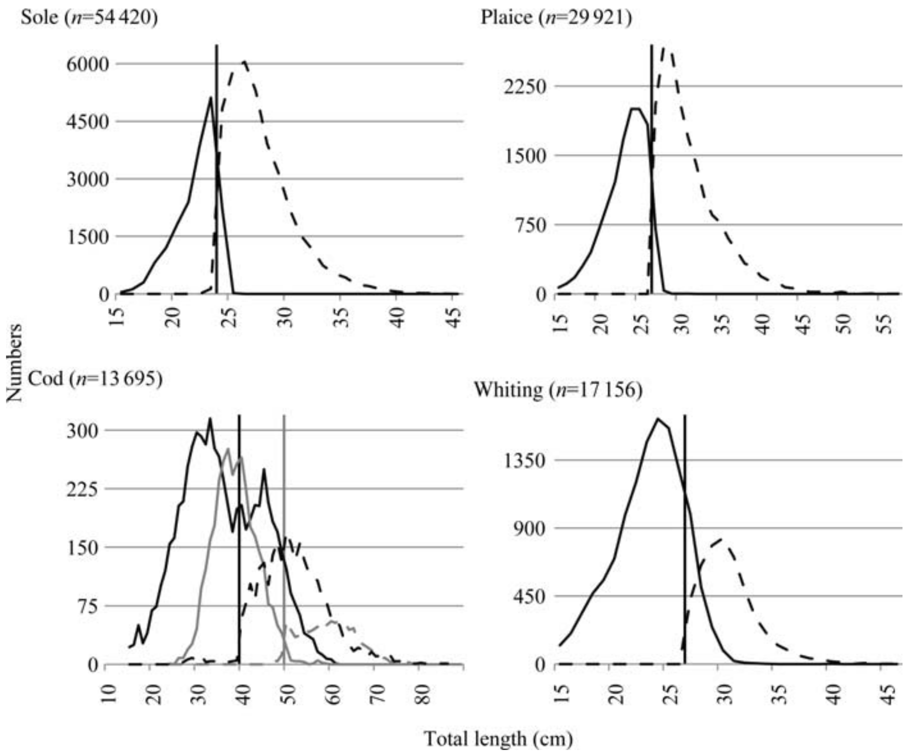

Figure 2. Smoothed LFDs of sole, plaice, cod, and whiting for the discarded (solid) and landed fractions (dashed) based on on-board observations of the Belgian beam-trawl fishery in the southern North Sea between 2006 and 2008. The MLS is indicated by a vertical line (24 cm for sole, 27 cm for plaice and whiting; it changed for cod from 40 to 50 cm on 1 July 2008). LFDs are shown before (black) and after (grey) this change. *n* is the number of fish measured.

Table 3. Mean proportion (and s.d.) of cod and whiting above MLS discarded in the Belgian beam-trawl fishery in the southern North Sea by quarter in the years 2006–2008.

	Highgraded proportion of discards per quarter			
Year	**Quarter 1**	**Quarter 2**	**Quarter 3**	**Quarter 4**
Cod				
2006	0.03 (0.09)	0 (0.01)	0	0.04 (0.08)
	0.04 (0.09)	0.01 (0.02)	0	0.04 (0.09)
2007	No data	0.01 (0.05)	0.05 (0.11)	0.47 (0.35)
		0.01 (0.04)	0.06 (0.11)	0.37 (0.32)
2008	0.62 (0.25)	0.28 (0.26)	0.02 (0.06)	0.03 (0.13)
	0.49 (0.22)	0.31 (0.24)	0.04 (0.09)	0.03 (0.14)
Whiting				
2006	0.17 (0.24)	0.07 (0.07)	0.18 (0.13)	0.23 (0.18)
	0.18 (0.23)	0.08 (0.04)	0.22 (0.08)	0.22 (0.14)
2007	No data	0.12 (0.13)	0.15 (0.09)	0.16 (0.11)
		0.12 (0.11)	0.23 (0.06)	0.20 (0.05)
2008	0.10 (0.12)	0.32 (0.24)	0.18 (0.08)	0.17 (0.13)
	0.15 (0.11)	0.37 (0.22)	0.26 (0.09)	0.23 (0.16)

Upper rows, number-based highgraded proportion; lower rows, weight-based proportion.

(Figure 3). Five fishing trips (120 hauls) yielded landings of at least 15% cod, and on three fishing trips (58 hauls), the landings included <75% of listed species.

None of the examined explanatory variables in the GLMM could explain the variation in the response variable $[D_{\text{obs}}/(D_{\text{obs}} + D_{\text{estim}})]$ for whiting, demonstrating that discarding of whiting above MLS was not the result of a variation in fish price, LPT, or the catch composition. Backward selection of the fixed-effect variables for cod resulted in a model with LPT as the only significant variable ($F = 6.806$, d.f. = 1.486, $p < 0.001$). The smoother had 1.486 effective degrees of freedom, indicating a nearly linear decreasing trend of the response as a function of LPT (Figure 4). However, the adjusted r^2 is 0.28, indicating that the explanatory power of the model is limited.

Discussion

Here we investigated the discarding behaviour of the Belgian beam-trawl fishery in the southern North Sea. Sole and plaice were highgraded, but the low quantities demonstrate that highgrading is unimportant. Cod above MLS are possibly discarded as a consequence of LPT restrictions, whereas discards of whiting above MLS cannot be attributed to seasonal changes in fish price, LPT limitations, or catch composition. Estimating the discard rates of sole and plaice from LFDs and MLS is therefore proposed for the Belgian beam-trawl fishery in the southern North Sea, but additional factors need to be considered if discard rates are to be estimated for cod and whiting.

Highgrading and discard estimates of target species

The observed and estimated discard rates for all species were significantly different, although only a limited quantity of sole and plaice above MLS was discarded and just few undersized sole and plaice were landed. These differences are more likely attributable to the visual sorting process. For example, fishers may unintentionally discard plaice 27 cm long and retain undersized fish.

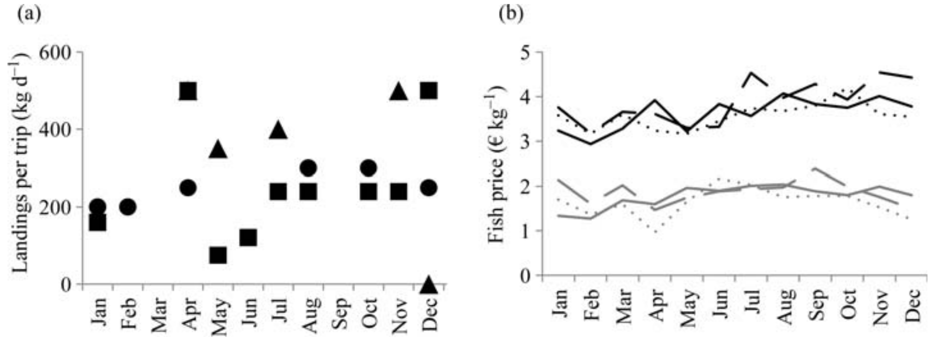

Figure 3. (a) Cod LPT are represented by month for each trip sampled in 2006 (square), 2007 (triangle), and 2008 (circle). (b) Variation of fish prices by month for cod (black) and whiting (grey) in 2006 (solid line), 2007 (dashed line), and 2008 (dotted line). *Source*: Belgian Fisheries Service.

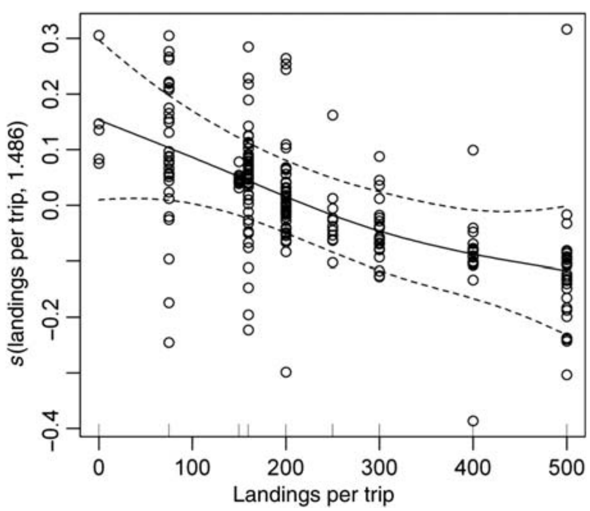

Figure 4. Non-linear smooth relationship between LPT and the response variable in the final GAMM model for cod. The dotted lines are the 95% confidence intervals.

The limited landings of undersized fish and discards of fish above MLS contributed to the differences between the observed and estimated discard rates. Therefore, we conclude that highgrading of sole and plaice is negligible in the Belgian beam-trawl fishery in the southern North Sea.

Kell and Bromley (2004) hypothesized that differences in highgrading can be explained largely by the interplay of targeting behaviour and LPT limitations. Targeting behaviour depends on species abundance and fish price (Gillis *et al*., 2008), so is indicated by the total landed value. The proportion of landed value was 49–53% for sole, 11–13% for plaice, 4–5% for cod, and <1% for whiting for the Belgian fishing fleet in the period 2006–2008. Assuming sole and plaice to be real target species for the Belgian beam trawlers in the southern North Sea, this study might indicate that fishers can eliminate highgrading of target species. For example, the choice of fishing grounds may preclude highgrading, with relative abundances of target species matched with availability of LPT (Gillis *et al*., 2008; Quirijns *et al*., 2008). If an excessive quantity of marketable plaice is caught, fishers may redirect fishing effort towards patches of lesser abundance. Bromley (2000) similarly suggested that if marketable plaice are of low value (as is typical in early spring), fishing effort is reduced.

In contrast to these findings, highgrading of plaice has been suggested to take place when the largest size classes are in poor condition. Highgrading low-value fish, typically done in early spring, is meant to save LPT for high-value fish at the end of the year (Poos *et al*., 2010). The monthly plaice landings of the Belgian beam-trawl fishery ranged between 2 and 7% of the annual total from February to August, and between 10 and 18% from September to December. Combining these results with Figure 2 seems to confirm that Belgian fishers do not highgrade plaice in the southern North Sea. Interestingly, this contrasts with the results from the Dutch beam-trawl fishery. A possible explanation lies in the overlap between the spatial distribution of plaice and fishing effort. Landings of the Belgian beam-trawl fishery in the southern North Sea primarily originate in fishing grounds with a rocky seabed along the western part of ICES Division IVc (Figure 1). Dutch beam trawlers mostly operate in the southeastern and central North Sea (Poos and Rijnsdorp, 2007), where plaice abundance is greater (Bogaards *et al*., 2009). However, avoiding LPT limitations on plaice could also be realized by misreporting plaice catches to a bordering ICES Division with unfulfilled LPT (B. Deputter, pers. comm.). Finally, the differences in discarding behaviour could be due to an observer effect, which has been demonstrated in the Gulf of St Lawrence (Benoît and Allard, 2009). Perhaps Belgian fishers chose not to highgrade sole and plaice because of the observers' presence. A *post hoc* analysis of this effect is difficult to address quantitatively within the current design of the discard-sampling programme (Benoît and Allard, 2009), so was not tested in this study. However, the potential observer effect implies the need for caution when drawing conclusions on the apparent lack of highgrading of sole and plaice in the beam-trawl fishery. Understanding the preconditions of the fishery is advisable if sole and plaice discards are estimated from LFD and MLS.

Highgrading and discard estimates of bycatch species

Discard rates of bycatch species must account for market- and management-induced variability. Species with low abundance and value lack profitability, so are more likely to be highgraded. This statement was formally tested for whiting, which was highgraded in nearly all quarters (Table 3), independent of LPT restrictions. Stratoudakis *et al*. (1998) obtained similar findings for demersal trawlers and seiners catching low-value gadoids. For bycatch species with low profitability, LPT was not the main limitation. Vessel-storage capacity and/or catch composition should reveal the incentives for highgrading, especially when low-value species are discarded to make space for more profitable fish (Gillis *et al.*, 1995b), when catches of target species are below expectations (Redant and Polet, 1994), or when legislation requires the bulk of the landings to be of the target species (Catchpole *et al.*, 2008; Benoît and Allard, 2009). The analysis of highgraded whiting in this study did not indicate catch composition at the trip level as an important driver. However, examining the variability of catch composition on a haul-by-haul basis might uncover a relationship between catch composition and highgrading of bycatch species. Our analysis shows substantial cod discarding above MLS during periods with stringent LPT limitations. Catch-composition requirements might also have influenced highgrading, but a haul-by-haul approach for detecting this effect is again preferable. Owing to the lack of landings and discards data by haul, however, that hypothesis could not be tested.

Management implications

This study has indirect implications for fishery management. First, it indicates that estimation of discard rates may complement the data available from discard observer programmes. This could lead to improved stock assessment and advice on total allowable catches. A protocol for such estimates should require that commercial species be regulated by MLSs, and that LFDs of the catch using a particular fishing gear can be estimated for the species under investigation. One conceivable way of collecting those LFDs would be to involve fishers along with electronic monitoring and automated observations of fish species and lengths using a digital camera (White *et al.*, 2006; Benoît and Allard, 2009). Another way to obtain LFDs of fish catches using commercial gear would be through combining abundance estimates and selectivity parameters (Piet *et al.*, 2009). As LFDs for each type of fishing gear and fish species can be collected more easily than actual discard data, their spatial and temporal range could be expanded considerably. However, estimates would need to be verified against observed discard rates from observer programmes, because variability in discarding can also result from market- and management-induced factors (Rochet and Trenkel, 2005). Such a protocol, when applied to the Belgian beam-trawl fishery in the southern North Sea, would result in justifiable estimates for the target species (sole and plaice). For highly profitable bycatch species (e.g. cod), LPT incentives need to be accounted for when making an estimate. For bycatch species with low profitability (e.g. whiting), LPT and seasonal variations in fish price cannot explain the variation in discarding. For low-value species, a more-detailed investigation of discard-variability factors, such as fishers' behaviour in response to catch composition, is needed.

Second, specifying the drivers of discard variability expedites the identification of discard-mitigation measures and the evaluation of introduced actions (Borges *et al.*, 2006; Enever *et al.*, 2009). Whiting is a clear example where gear selectivity needs to be changed to avoid the conditions leading to highgrading. Highgrading takes place in nearly all quarters, although there are feasible techniques that reduce catches of whiting without major losses of sole and plaice (van Marlen, 2003). In addition to establishing factors of discard variability and mitigating the causes, these results need to be followed up. Only in this way will fishery management have any hope of succeeding (Graham *et al.*, 2007; Enever *et al.*, 2009).

Acknowledgements

We thank the shipowners, crew, and on-board observers for their assistance in the ILVO discard sampling programme. The research was facilitated by information from the Administrative Centre of the Department for Agriculture and Fisheries of the Flemish Government (Eddy Tessens). We are also indebted to Stefan Van Dongen for helpful discussions and valuable suggestions on the statistical analyses, and to Miriam Levenson for grammatical polishing. We also acknowledge the inputs of the *Journal* guest and in-house editor and two anonymous referees, for advice that considerably improved the quality of this paper. The study was partly carried out within the WAKO-II project, funded by Contract SD/NS/08A of the Belgian Science Policy. Further support for the work was provided by the Flemish Government and the European Commission (through the Data Collection Framework).

References

Aarts, G., and Poos, J. J. 2009. Comprehensive discard reconstruction and abundance estimation using flexible selectivity functions. ICES Journal of Marine Science, 66: 763–771.

Benoît, H. P., and Allard, J. 2009. Can the data from at-sea observer surveys be used to make general inferences about catch composition and discards? Canadian Journal of Fisheries and Aquatic Sciences, 66: 2025–2039.

Bogaards, J. A., Kraak, S. B. M., and Rijnsdorp, A. D. 2009. Bayesian survey-based assessment of North Sea plaice (*Pleuronectes platessa*): extracting integrated signals from multiple surveys. ICES Journal of Marine Science, 66: 665–679.

Borges, L., Zuur, A. F., Rogan, E., and Officer, R. 2006. Modelling discard ogives from Irish demersal fisheries. ICES Journal of Marine Science, 63: 1086–1095.

Bromley, P. J. 2000. Growth, sexual maturation and spawning in central North Sea plaice (*Pleuronectes platessa* L.), and the generation of maturity ogives from commercial catch data. Journal of Sea Research, 44: 27–43.

Catchpole, T. L., Frid, C. L. J., and Gray, T. S. 2005. Discards in North Sea fisheries: causes, consequences and solutions. Marine Policy, 29: 421–430.

Catchpole, T. L., van Keeken, O., Gray, T., and Piet, G. 2008. The discard problem—a comparative analysis of two fisheries: the English *Nephrops* fishery and the Dutch beam trawl fishery. Ocean and Coastal Management, 51: 772–778.

Cotter, A. J. R., and Pilling, G. M. 2007. Landings, logbooks and observer surveys: improving the protocols for sampling commercial fisheries. Fish and Fisheries, 8: 123–152.

Dickey-Collas, M., Pastoors, M. A., and van Keeken, O. A. 2007. Precisely wrong or vaguely right: simulations of noisy discard data and trends in fishing effort being included in the stock assessment of North Sea plaice. ICES Journal of Marine Science, 64: 1641–1649.

EC (European Commission). 1998. Council Regulation (EC) No. 850/98 of 30 March 1998 for the conservation of fishery resources through technical measures for the protection of juveniles of marine organisms. Official Journal of the European Communities, L125/1. 36 pp.

EC (European Commission). 2000. Council Regulation (EC) 1543/2000 of 29 June 2000 establishing a Community framework for the collection and management of the data needed to conduct the common fisheries policy. Official Journal of the European Communities, L176/1. 16 pp.

EC (European Commission). 2009. Commission Regulation (EC) No. 409/2009 of 19 May 2009 establishing Community conversion factors and presentation codes used to convert fish processed weight into fish live weight, and amending Commission

Regulation (EEC) No. 2807/83. Official Journal of the European Union, L123/78. 78 pp.

Enever, R., Revill, A. S., and Grant, A. 2009. Discarding in the North Sea and on the historical efficacy of gear-based technical measures in reducing discards. Fisheries Research, 95: 40–46.

Gillis, D. M., Peterman, R. M., and Pikitch, E. K. 1995a. Implications of trip regulations for high-grading; a model of the behavior of fishermen. Canadian Journal of Fisheries and Aquatic Sciences, 52: 402–415.

Gillis, D. M., Pikitch, E. K., and Peterman, R. M. 1995b. Dynamic discarding decisions: foraging theory for high-grading in a trawl fishery. Behavioral Ecology, 6: 146–154.

Gillis, D. M., Rijnsdorp, A. D., and Poos, J. J. 2008. Behavioral inferences from the statistical distribution of commercial catch: patterns of targeting in the landings of the Dutch beam trawler fleet. Canadian Journal of Fisheries and Aquatic Sciences, 65: 27–37.

Graham, N., Ferro, R. S. T., Karp, W. A., and MacMullen, P. 2007. Fishing practice, gear design, and the ecosystem approach—three case studies demonstrating the effect of management strategy on gear selectivity and discards. ICES Journal of Marine Science, 64: 744–750.

Kell, L. T., and Bromley, P. J. 2004. Implications for current management advice for North Sea plaice (*Pleuronectes platessa* L.). 2. Increased biological realism in recruitment, growth, density-dependent sexual maturation and the impact of sexual dimorphism and fishery discards. Journal of Sea Research, 51: 301–312.

Kelleher, K. 2005. Discards in the world's marine fisheries. An update. FAO Fisheries Technical Paper, 470. 131 pp.

Liggins, G. W., Bradley, M. J., and Kennelly, S. J. 1997. Detection of bias in observer-based estimates of retained and discarded catches from a multispecies trawl fishery. Fisheries Research, 32: 133–147.

Piet, G. J., van Hal, R., and Greenstreet, S. P. R. 2009. Modelling the direct impact of bottom trawling on the North Sea fish community to derive estimates of fishing mortality for non-target fish species. ICES Journal of Marine Science, 66: 1985–1998.

Polet, H., Andersen, B. S., Buisman, E., Catchpole, T. L., Depestele, J., Madsen, N., Piet, G., *et al.* 2010. Studies and pilot projects for carrying out the Common Fisheries Policy. LOT 3: scientific advice concerning the impact of the gears used to catch plaice and sole. Report submitted to the Director-General for Fisheries and Maritime Affairs, European Commission. http://www.vliz.be/imis/imis.php?module=ref&refid=200444.

Poos, J. J., Bogaards, J. A., Quirijns, F. J., Gillis, D. M., and Rijnsdorp, A. D. 2010. Individual quotas, fishing effort allocation, and over-quota discarding in mixed fisheries. ICES Journal of Marine Science, 67: 323–333.

Poos, J. J., and Rijnsdorp, A. D. 2007. The dynamics of small-scale patchiness of plaice and sole as reflected in the catch rates of the Dutch beam trawl fleet and its implications for the fleet dynamics. Journal of Sea Research, 58: 100–112.

Quirijns, F. J., Poos, J. J., and Rijnsdorp, A. D. 2008. Standardizing commercial cpue data in monitoring stock dynamics: accounting for targeting behaviour in mixed fisheries. Fisheries Research, 89: 1–8.

Redant, F., and Polet, H. 1994. Results of discard study on the Belgian *Nephrops* fishery in central North Sea. ICES Document CM 1994/K: 44.

Rochet, M-J., Péronnet, I., and Trenkel, V. M. 2002. An analysis of discards from the French trawler fleet in the Celtic Sea. ICES Journal of Marine Science, 59: 538–552.

Rochet, M-J., and Trenkel, V. M. 2005. Factors for the variability of discards: assumptions and field evidence. Canadian Journal of Fisheries and Aquatic Sciences, 62: 224–235.

Stratoudakis, Y., Fryer, R. J., and Cook, R. M. 1998. Discarding practices for commercial gadoids in the North Sea. Canadian Journal of Fisheries and Aquatic Sciences, 55: 1632–1644.

van Marlen, B. 2003. Improving the selectivity of beam trawls in The Netherlands: the effect of large mesh top panels on the catch rates of sole, plaice, cod and whiting. Fisheries Research, 63: 155–168.

Welch, D. J., Mapstone, B. D., and Begg, G. A. 2008. Spatial and temporal variation and effects of changes in management in discard rates from the commercial reef line fishery of the Great Barrier Reef, Australia. Fisheries Research, 90: 247–260.

White, D. J., Svellingen, C., and Strachan, N. J. C. 2006. Automated measurement of species and length of fish by computer vision. Fisheries Research, 80: 203–210.

Wood, S. N. 2006. Low rank scale invariant tensor product smooths for generalized additive mixed models. Biometrics, 62: 1025–1036.

Zuur, A. F., Ieno, E. N., Walker, N. J., Saveliev, A. A., and Smith, G. 2009. Mixed Effects Models and Extensions in Ecology with R. Springer, New York. 574 pp.