Original Article

Estimating efficiency of survey and commercial trawl gears from comparisons of catch-ratios

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Assumptions about gear efficiency and catchability influence estimates of abundance, mortality, reference points and catch potential. Despite the need to better quantify fishing effects on some target species and on many non-target species taken as bycatch, there are few gear efficiency estimates for some of the most widely deployed towed fishing gears in the northeast Atlantic. Here, we develop a method that applies generalised additive models to catch-at-length data from trawl surveys and a commercial catch and discard monitoring program in the North Sea to estimate catch-ratios. We then rescale these catch-ratios and fit relationships to estimate gear efficiency. When catches of individuals by species were too low to enable species-specific estimates, gear efficiency was estimated for species-groups. Gear efficiency (and associated uncertainty) at length was ultimately estimated for 75 species, seven species-groups and for up to six types of trawl gear per species or species-group. Results are illustrated for dab (*Limanda limanda*), grey gurnard (*Eutrigula gurnardus*) and thornback ray (*Raja clavata*), two common non-target species and a depleted elasmobranch. All estimates of gear efficiency and uncertainty, by length, species, species-group and gear, are made available in a supplementary data file.

Keywords: availability, beam trawl, catchability, gear efficiency, monitoring, North Sea, otter trawl, towed gear.

Introduction

Bottom trawl fisheries targeting a few commercially valuable species often catch many non-target species. A variable proportion of these species may be discarded, depending on characteristics of the fishery, management system and species' individual size and value. Historically, the low landings volume or low commercial value of most non-target species meant that there was relatively little focus on the impact of fishing and species' status, although trends in relative abundance were often reported from areas where monitoring surveys took place (e.g. Heessen and Daan, 1996). More recently, there are stronger drivers for reporting sensitivity and status of these species. Reasons are (i) the emergence of legal requirements to define sustainable rates of fishing for more of the species impacted by fishing, (US, 2006; EC, 2013), (ii) concern that some of these species are at risk of population collapse owing to high sensitivity to fishing mortality (Brander, 1981; Walker and Hislop, 1998; Dulvy *et al.*, 2000) and (iii) the

need to better understand and manage the effects of fishing on food webs, biodiversity and ecosystems to meet emerging policy requirements (EC, 2008a, 2010; CBD, 2010).

Commercial and research fishing hauls could be used to estimate the distribution and abundance of non-target species (Poos *et al.*, 2013); however, the main challenge is that only a proportion of individual animals are caught by the fishing gear. Catchability describes the difference in abundance and size composition between the catch and the population, and can be used to convert relative abundance estimates from surveys to absolute abundance, to estimate fishing mortality rates and to establish fishing mortality or biomass reference points (e.g. Sparholt, 1990; Quinn and Deriso, 1999; Fraser *et al.*, 2007; Piet *et al.*, 2009; Shephard *et al.*, 2015). Catchability is a function of fish availability and gear efficiency (Walsh, 1996; Trenkel and Skaug, 2005; Zhou *et al.*, 2014). Availability is the accessibility of fish to a given gear and depends on the horizontal and vertical distribution of

fish in relation to the trawl at the time deployment (Walsh, 1996). Gear efficiency is the probability that fish in the path of a trawl will be caught and retained (Somerton *et al.*, 1999; Zhou *et al.*, 2014), and is determined by gear specification, deployment and performance as well as fish characteristics such as size, morphology and behaviour (Fraser *et al.*, 2007). Consequently, gear efficiency is expected to vary less than availability and catchability when a gear is deployed at different times and in different areas.

Despite the need to better quantify the effects of fishing on some target and many non-target species, there are few catchability or gear efficiency estimates for most species caught by commercial bottom-fishing gears in the northeast Atlantic, although Fraser *et al.* (2007) have published estimates for the Grande Overture Vertical (GOV) survey trawls used in the International Bottom Trawl Surveys (IBTS; ICES, 2012). Here, we develop a method that uses catch-at-length data collected in the IBTS, the Beam Trawl Survey (BTS; ICES, 2009) and a catch and discard monitoring program (Enever *et al.*, 2009) to determine the efficiencies of survey and commercial towed trawl gears in the North Sea. In this region, demersal trawl fisheries account for 95% of fishing effort (STECF, 2014) and, as mixed fisheries, catch a wide range of non-target species (Paramor *et al.*, 2009; Quirijns and Pastoors, 2014). These factors make the North Sea an ideal case study for developing and applying our method. Because we determine gear efficiency, rather than overall catchability, the efficiencies that we derive are potentially applicable to other regions. Since the North Sea survey and discard monitoring programmes record catches of both target and non-target species, we can apply the method to the majority of species directly impacted by fishing.

Material and methods

Catchability ($q_{s,l}$) links catch ($C_{s,l}$) to the true total population abundance ($N_{s,l}$):

$$q_{s,l} = a_{s,l} Q_{s,l} \tag{1}$$

$$\frac{C_{s,l}}{E} = q_{s,l} N_{s,l} \tag{2}$$

where $a_{s,l}$ is the availability and $Q_{s,l}$ is the gear efficiency on species s at length l and E is the fishing effort.

E is defined here as the area swept by a trawl net, $C_{s,l}/E$ is the catch per unit area (cpua) and catchability ($q_{s,l}$) is the proportion of the total population at a given length caught per unit swept area. Catchability is a product of fish availability ($a_{s,l}$) and gear efficiency ($Q_{s,l}$) ((1); Walsh, 1996; Trenkel and Skaug, 2005; Zhou *et al.*, 2014) and varies in time and space, owing largely to changes in availability. Gear efficiency for a given species at length, on the other hand, is expected to be rather more stable because it is a property of the physical characteristics and deployment of the gear. By accounting for differences in species distribution in time and space we can separate availability ($a_{s,l}$) from overall catchability ($q_{s,l}$) and estimate the probability that fish of a given species and length are captured when they are available to the fishing gear ($Q_{s,l}$). This has been termed gear efficiency (also referred to as fishing power, catch efficiency, catchability, or available selection by other authors, e.g. Casey and Myers, 1998; Millar and Fryer, 1999; Benoît and Swain, 2003;

Fraser *et al.*, 2007; Heino *et al.*, 2011). A three-stage process was used to estimate gear efficiency by species (or species group) at length from the catch recorded in survey and commercial trawls: (i) catch ratios of mean cpua between trawl gears by species and size class were estimated using generalized additive models (GAMs) to account for differences in species availability in time and space, (ii) catch ratios by species (or species-group) and size class were scaled to absolute gear efficiencies based on abundance estimates for assessed species and (iii) relationships, and associated uncertainty, to describe gear efficiency by species (or species-group) as a function of length were fitted to for each gear.

Data sources and processing

Our method was applied to catch data collected in the North Sea (ICES Area IV) between 2002 and 2015. Data were collated from the IBTS and BTS and a commercial discard observer programme. The North Sea IBTS uses a GOV otter trawl, takes place in quarters 1 and 3, and covers the entire North Sea, Skagerrak and Kattegat, and the eastern English Channel (ICES, 2012). The BTS uses beam trawls 4–8 m wide, takes place in quarter 3 and covers the southern, central and part of the northern North Sea, as well as the eastern English Channel and parts of the Celtic and Irish Seas (ICES, 2009). Data from the two surveys were downloaded from the ICES Database of Trawl Surveys (DATRAS; http://datras.ices.dk) on 20-05-2016.

Commercial data came from the Centre for Environment, Fisheries and Aquaculture Science (UK) observer programme, which places scientific observers on board commercial fishing vessels during regular operation. The programme has monitored catches of English and Welsh fishing vessels since 2002, sampling around 200 trips and 1200 hauls per year with a sampling coverage of 0.5–1% (Catchpole *et al.*, 2011). Towed trawl gears reported in the commercial data were grouped into six gear categories based on mesh size, following métier definitions from the Scientific, Technical and Economic Committee for Fisheries (STECF) of the European Union (EC, 2008b). A summary of the gear categories covered by the survey and commercial data is given in Table 1, and a map of trawl locations in Figure 1. Commercial beam and otter trawls not covered by the STECF métier groupings were excluded from this analysis, as these categories include unregulated gear types and contribute less fishing effort (STECF, 2014).

All fish caught in the surveys and the discard observer programme are identified to species, or to the lowest possible taxonomic level when species cannot be identified at sea, and their length recorded. Standard data recorded in the survey and discard databases include the catch of each species by length class, haul location, gear geometry, and the duration, speed and distance of hauls. Several steps were taken to clean the data: removal of data for hauls outside of the North Sea (ICES Area IV); deletion of hauls where information on catches or gear deployment was missing; deletion of hauls with clear outliers in the data used to calculate swept area; and removal of data for deep-water species, non-fish species, groups not identified to species and fish smaller than 5 cm (which are badly selected by trawls). To standardise estimates of fishing effort, an estimate of the area swept by the gear for each trawl was calculated. Swept area was calculated as wingspread (otter trawls) or beam width (beam trawls) multiplied by the distance towed. If information on the distance towed was not available, swept area was estimated as wingspread multiplied by the product of haul duration and ground speed (Fung *et al.*,
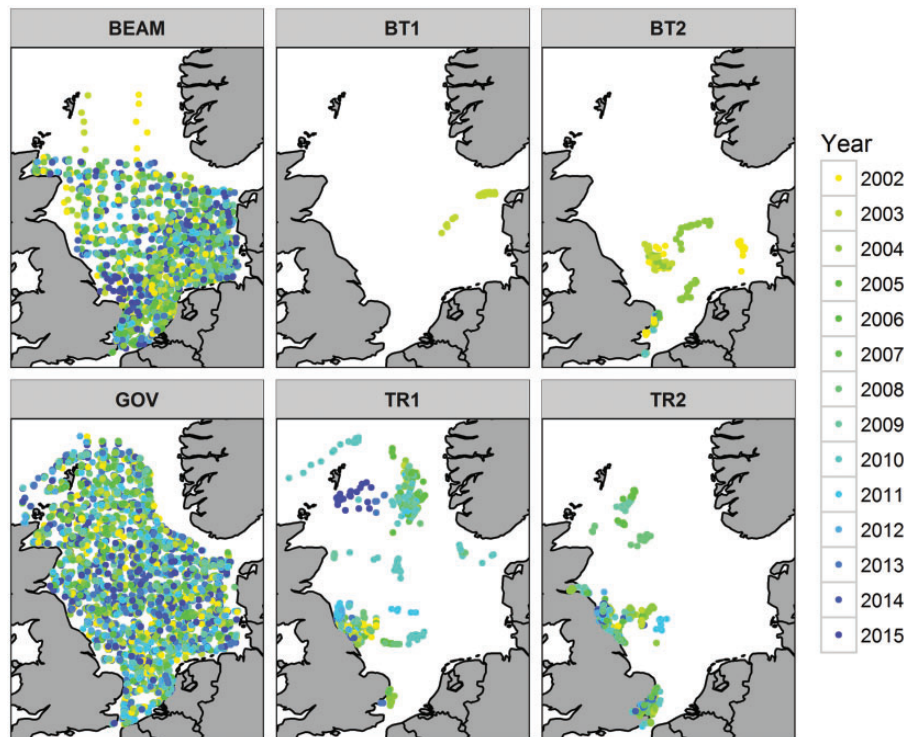
Figure 1. The spatiotemporal distribution of trawls in the North Sea for the IBTS (GOV), BTS (BEAM) and Cefas discard observer programme (TR1, TR2, BT1 and BT2) between 2002 and 2015.

Table 1. Gear categories defined in this study.

Gear code	Gear type	Purpose	Mesh size	Number of hauls
GOV	Grande Overture Vertical	Survey	–	8596
BEAM	Beam trawl	Survey	–	3101
TR1	Otter trawl	Commercial	$\geq 100\,mm$	868
TR2	Otter trawl	Commercial	$70 \leq mesh < 100\,mm$	1209
TR*	Otter trawl	Commercial	$< 70\,mm$	–
BT1	Beam trawl	Commercial	$\geq 120\,mm$	66
BT2	Beam trawl	Commercial	$80 \leq mesh < 120\,mm$	331
BT*	Beam trawl	Commercial	$< 80\,mm$	–

Gears marked with an asterisk were recorded in the catch and discard monitoring data but excluded from this analysis.

2012). If information on otter trawl geometry was missing, estimates of wingspread were obtained from an average of nearby records or published relationships between wingspread and depth (Fraser *et al.*, 2007; Fung *et al.*, 2012).

Gear efficiency could not be calculated for all individual species due to the limited number of observations for some species. To generate estimates of gear efficiency that could be applied to all species, all species were grouped into species groups based on body shape, behaviour, habitat preferences and typical position in the water column (Table 2; Supplementary material, Table S1); these traits are expected to affect the gear efficiency for a given species (Fréon *et al.*, 1993). Therefore, species within a species group are expected to have similar gear efficiency at size. The method for estimating gear efficiency was applied both to individual species and to each of the species groups.

Catch ratios

When gear efficiency and catchability are confounded due to spatial variation in abundance (1) and the true abundance of species

is not known, direct estimates of gear efficiency cannot be obtained from (2), but the ratio of cpuas can be used to measure the relative gear efficiency of any pair of gears:

$$\frac{C_{s,l,1}/E_1}{C_{s,l,2}/E_2} = \frac{a_{s,l,1}\,Q_{s,l,1}}{a_{s,l,2}\,Q_{s,l,2}} \tag{3}$$

where the numeric subscripts represent gear type (1 or 2) and the right-hand side of the equation shows the confounding of availability and gear efficiency. Catch ratios, giving relative gear efficiencies, were estimated using GAMs to separate the influence of spatial and temporal patterns in the density of fish available from gear efficiency.

The observed data provided the number of fish caught $C_{i,s,l}$ of species s at length, for each tow i, along with the fishing gear used g, tow location, date and swept area E. As both survey and commercial sampling programmes record catches of all fish species, a row representing zero catch was added to the data set when a species was not reported in a haul. Individual fish were assigned to

Table 2. Species groups defined in this study.

Species group	Group description
1	Predominantly buried in sediment
2	On or near the seabed—anguilliform or fusiform
3	Predominantly on the seabed—flat
4	Predominantly close to the seabed, but not on it
5	Midwater species with some seabed association
6	Pelagic
7	Predominantly on the seabed—lumpiform

5 cm length classes (l) by species or species-groups, with the exception of smaller species which would not be adequately described by such a grouping. Locations were converted from longitude and latitude to easting and northing (x, y) (using R function spTransform with CRS espg:27700); dates (t) were defined as days from 31-12-2001.

For each species' length class, catch numbers were modelled as a smoothly varying function of location and date, with a scaling factor for each gear, and log (swept area) defined as the model offset to convert from catch numbers to catch per unit area (cpua). Fitting models separately by length class allowed for potential spatial separation of different components of the population, e.g. adults and pre-recruits, and reduced individual model complexity. A negative binomial distribution with a log link was used because of the skewed distribution of catch numbers which had 17 to 99% of zero values for individual species:

$$C_{i,s,l} \sim \text{negative binomial}(\mu_{i,s,l}, \ \theta) \qquad (4)$$

$$\log(\mu_{i,s,l}) = te_{s,l}(x_i, y_i, t_i) + g_{i,s,l} + \log(E_i) \qquad (5)$$

where te was a three-dimensional tensor product smoother (as location and date are on different scales). Gear (g) was a factor, therefore, a reference gear was specified with its coefficient set to zero as a model fitting constraint. This gear was the GOV when it had positive catches as it is a survey gear with wide spatial coverage (Figure 1). Otherwise, the reference gear was the first with catches in the sequence: BEAM, BT1, BT2, TR1 and TR2.

After model fitting, the gear coefficients $\beta_{g,s,l}$ were extracted and back transformed $r_{g,s,l} = \exp(\beta_{g,s,l})$ to give the efficiency of each gear relative to the reference gear (relative efficiency).

More than one gear with positive catches was needed to estimate catch ratios and a total of at least ($10 + $ number of gears) observations to estimate all the coefficients. Species' length classes not meeting these criteria were excluded. Fitting was carried out using the function *gam* with *family* = *nb*, from mgcv package v1.8-9 (Wood, 2006) in R 3.2.3 (R Development Core Team, 2015). Model checking consisted of residual plots, comparison of the smoothing degrees of freedom against the basis dimension and plots of predictions at representative locations and dates.

Absolute gear efficiency

Estimates of relative gear efficiency were converted to estimates of absolute gear efficiency in two stages. First, for each species or species-group, the efficiency of the gear with the highest relative efficiency for a length class was set to one, and the efficiency for other gears scaled in proportion to their relative efficiencies to ≤1. Since no trawl catches all of the fish in its path, these efficiencies may overestimate absolute efficiency. Second, to estimate absolute efficiency, we applied multipliers to scale the efficiencies by comparing abundance estimates generated with the unscaled estimates of gear efficiency with independent estimates of total species abundance in the North Sea from stock assessments (Sparholt, 1990; Fraser *et al.*, 2007).

Quantitative stock assessments are carried out for relatively few species. Since the aim of our analysis is to estimate gear efficiency for all fish species, but particularly non-target species for which routine stock assessments are not performed, we used multipliers for the commercial species to define multipliers for other species in the same species groups (Table 2). Assessed species considered were: sole (species-group 1), plaice (3), cod (4), Norway pout (5) and herring (6). Assessed species in groups 2 and 7 were not considered suitable representatives of their species-group, either because they are classified as widely distributed stocks or are assessed using qualitative methods. The multipliers of species groups 2 (on or near the seabed—anguilliform or fusiform) and 7 (predominantly on the seabed—lumpiform) were, therefore, set to those for groups 4 (predominantly close to the seabed, but not on it) and 3 (predominantly on the seabed—flat), respectively.

Estimated numbers from survey trawl data

The number of each assessed species, except sole, was estimated using the first-stage estimates of absolute efficiency ($\hat{Q}_{s,l}$) and the IBTS survey data, because the IBTS provides almost complete coverage of the North Sea (Figure 1). BTS survey data were used for sole because it is not effectively sampled by the IBTS and its distribution is almost exclusively within the BTS area. When individuals are assumed to be randomly or evenly distributed within an area A availability is equal to unity and, with $1 \, \text{km}^2$ as our unit of fishing effort, (1) reduces to $q_{s,l} = Q_{s,l}/A$, where $1/A$ is the constant of proportionality between catchability and efficiency (Somerton *et al.*, 1999; Zhou *et al.*, 2014). Substituting this into (2), making the assumption that availability is constant within ICES rectangles, cpuas ($C_{s,l,r}/E_r$) for each assessed species in a given length class caught in a given rectangle were scaled to take account of gear efficiency ($\hat{Q}_{s,l}$). These scaled cpuas were converted to survey-based estimates of total numbers ($\hat{N}_{s,l}$) by multiplying mean scaled cpua per rectangle by the area of the rectangle (A_r) and summing the resulting abundance by rectangle across the North Sea (Fraser *et al.*, 2007):

$$\hat{N}_{s,l} = \sum_r A_r \left(\frac{1}{\hat{Q}_{s,l}} \frac{\overline{C_{s,l,r}}}{E_r} \right) \qquad (6)$$

Because the surveys do not sample every rectangle in the North Sea each year (ICES Area IV; Supplementary material, Figures S1–S3) raising factors were used to estimate the numbers expected had each rectangle been sampled. To allow for differences in biogeographical distributions of species, raising factors were calculated and applied for each year and each of five subareas (Fraser *et al.*, 2007) (Supplementary material, Figure S4 and Tables S2–4).

Numbers from stock assessments

Estimates of the numbers of fish-at-age in the North Sea are available from stock assessments carried out by the Working Group on the Assessment of Demersal Stocks in the North Sea and Skagerrak (WGNSSK) (ICES, 2015a) and the Herring Assessment

Working Group (HAWG) (ICES, 2016). Some of the North Sea stock assessments cover areas surrounding the North Sea as well as the body of the North Sea (ICES Area IVa–c), including the Skagerrak and Kattegat (ICES Area IIIa) and the Eastern Channel (ICES Area VIId). In these cases, assessment numbers were multiplied by the proportion of the assessment area inside the North Sea (ICES Area IVa–c) based on the simplifying assumption that mean numbers per unit area in the assessment area were the same inside and outside the North Sea (Supplementary material, Table S5).

Stock assessments provide numbers at age on the 1 January each year but the Q3 IBTS and BTS surveys are carried out from July to September. To account for the mortality that takes place between the assessment and the Q3 surveys the scaled catch data were compared with the assessment numbers ($N_{s,a}$) reduced by the fishing ($F_{s,a}$) and natural mortality ($M_{s,a}$) assumed to occur during this time period:

$$N_{Q3,s,a} = N_{Jan1,s,a} e^{-Y(M_{s,a}+F_{s,a})} \tag{7}$$

where Y is the length of the intervening period of as a proportion of the year (Fraser *et al.*, 2007). Here we used a value of $Y = 0.5$ to project the assessment numbers to the beginning of quarter 3 (1 July). Values of F and M were taken from the assessment reports (ICES, 2015a, 2016). We treat these as true estimates of abundance to apply our method, but recognise the estimates are subject to sources of error we do not consider and will be influenced by catch-data obtained from some of the gears we investigate. However, no entirely fishery independent absolute abundance estimates are available for target species in the North Sea.

Multipliers

Because the survey data are length based and the assessments age based, estimated numbers-at-length were converted to numbers-at-age using age–length keys (ALKs) obtained from DATRAS. However, for plaice and cod, survey-based ALKs were insufficient to describe larger fish (less than ten observations per length class across the years we consider; Coggins *et al.*, 2013). In these cases, the survey-based ALKs were combined with ALKs from observer sampling (Supplementary material, Figures S5–9). Multipliers for each year and quarter were obtained by dividing the survey-based estimates of numbers-at-age by assessment numbers-at-age (ICES, 2015a, 2016), and the final multiplier-at-age was taken as the mean among quarters and years. Multipliers-at-age were converted back to multipliers-at-length through application of inverse age–length keys (Loff *et al.*, 2014). A simple GAM model was used to fit gear efficiency multipliers as a smooth function of length, allowing multipliers for each length class of each species-group to be estimated (Supplementary material, Figure S10). These multipliers were then used to adjust the first stage estimates of absolute gear efficiency.

Gear efficiency curves

To estimate gear efficiency for all species' length classes, we established relationships between gear efficiency and length. Towed gear selection is effectively represented by parametric sigmoid or bell-shaped curves (Millar and Fryer, 1999; Huse *et al.*, 2000). However, as gear efficiency includes other processes in addition to gear selection (see Discussion section) non-parametric curves

were considered appropriate to capture the relationships while placing lower requirements on the data.

GAMs were used to model gear efficiency ($Q_{s,l}$) as a smooth function (f) of length (l) for each species (s):

$$Q_{s,l} = f_s(l) \tag{8}$$

GAMs were fit to the absolute efficiency estimates at the midpoint of 5cm length classes, or on 1cm length classes for small species whose lengths were not grouped, using thin plate regression splines with shrinkage (Wood, 2006). To avoid overfitting, a multiplier of 1.4 was used to inflate the degrees of freedom in the generalised cross validation score (Kim and Gu, 2004). GAMs were fit where three or more absolute efficiency estimates were available for a species and gear. Where only two absolute efficiency estimates were available the mean of those estimates is reported. Where one or no absolute efficiency estimates were available, the efficiency of that gear on a species is assumed the same as the species group.

Two modifications to the fitted curves were made to account for length classes falling outside the range of gear efficiencies represented:

$$Q_{s,l} = \begin{cases} \phi l, & l < l_{\text{lower}} \\ f_s(l), & l_{\text{lower}} \leq l \leq l_{\text{upper}} \\ f_s(l_{\text{upper}}), & l > l_{\text{upper}} \end{cases} \tag{9}$$

where l_{lower} and l_{upper} are the smallest and largest length classes for which absolute efficiency estimates are available, ϕ is a gradient parameter and $f_s(l)$ is the smooth GAM curve. These modifications were based on assumptions about the retention of small and large individuals. Fish smaller than 5cm were excluded from our analysis. Therefore, to account for the smallest individuals, a straight line from the origin to the value of the function at the smallest observed length class was assumed. Large fish may always remain somewhat vulnerable to fishing gears (Smith and Taylor, 2014), so where it was necessary to extrapolate efficiencies for large length classes the value of the smooth at the bound of the largest length class with an estimate was assumed.

Results

The gear efficiency analysis included 128 species (Supplementary material, Table S1). Here we illustrate results for dab (*Limanda limanda*), grey gurnard (*Eutrigula gurnardus*) and thornback ray (*Raja clavata*), two common non-target species and a depleted elasmobranch.

Data were sufficient to estimate catch ratios for 55% (720 of 1315) of observed species' length classes across 81 species using GAMs. Data from the GOV gear were included in 692 of these 720 models (96%), the remaining cases were for blonde ray (BLR), cuckoo ray (CUR), seabass (ESB) and the single length classes of 10 cm brill (BLL), 20 cm great sandeel (GSE) and 60 cm plaice (PLE). The combinations of gears included gave between 1265 and 14,171 hauls for the models (mean $n = 12,534$). Overall, the models were effective at describing the observations, with the mean deviance explained being 63% ($n = 720$ models, 2.5th percentile $= 32\%$, 97.5th percentile $= 89\%$), although occasional very high fish densities were not so well described.

The complexity of the fitted smoother varied between no trend for some less common species, e.g. 85 cm halibut (HAL; effective

degrees of freedom (edf) < 0.01), through to cases such as dab (15 cm, edf = 99.7; 20 cm, edf = 98.5) with multiple areas of higher density and gradual temporal trends (Figure 2). The majority of models showed spatial patterns with one or more centres of density within the study region (mean edf = 37.9, median edf = 32.5) and more complex surfaces were fitted for species-length class combinations with more observations. The negative binomial dispersion parameter (θ) tended to be small (median across the 720 models = 0.07; 1st, 25th, 75th and 99th percentiles of 0.003, 0.027, 0.175 and 1.043), reflecting cases with low average density and indicating that variance increased as density increased.

Figure 2 illustrates the process used to derive catch-ratios for the most abundant length class of each example non-target species (15 cm dab; 20 cm grey gurnard; 35 cm thornback ray). Patterns in the predicted temporal plots for dab and grey gurnard are broadly consistent with stock size indicators from qualitative assessments (ICES, 2015a), but the plot for thornback ray fails to pick up the increase in abundance noted in recent years (ICES, 2015b). Spatial predictions for all three species are broadly consistent with current knowledge of their distribution (Heessen et al., 2015; ICES 2015a,b).

The multipliers-at-age that scale the first stage absolute gear efficiency estimates (where the most efficient gear is set to 1) reflect the actual proportion of fish likely to be caught and retained, based on abundance estimates of assessed species (Table 3). The final efficiency curves for assessed species and survey gears show good overall correspondence to direct estimates of gear efficiency ((1) and (2); Supplementary material, Figure S11), with a slight overestimation of beam trawl efficiency for large sole and a slight underestimation of GOV efficiency for intermediate-sized cod.

Relationships between gear efficiency and length could be established for most species-groups and gears (Supplementary material, Figure S12). Species-groups 2 (on or near the seabed—anguilliform or fusiform), 5 (midwater species with some seabed association) and 6 (pelagic) with large-meshed beam trawl (BT1) were the only exceptions, as fewer than two absolute efficiency estimates were available across all observed length classes (up to 160 cm for species groups 2 and 5, and 220 cm for group 6). Gear efficiency could be estimated for 75 individual species. Of these, a full set of efficiencies could be determined for 16 species. For those species, where no efficiencies, or only a partial set, could be established gear efficiencies were assigned for the species-group. There were 24 species and gear combinations where the fitted curves dropped slightly below zero. In these cases (< 0.3%) the fitted efficiencies were set to zero. All relationships between gear efficiency and length are given in the supplementary .csv file and presented in Supplementary material, Figures S12–19, while Figure 3 provides an example of these outputs. For the species considered in the example, gear efficiency was estimated to be greatest for the commercial beam trawl (BT1) on dab and for the survey trawl (GOV) on grey gurnard. Both increasing and dome-shaped relationships between gear efficiency and length were observed. In the case of thornback ray, for instance, BEAM and TR2 were most efficient in the middle length classes, while GOV efficiency increased continuously with length.

Discussion

Our estimates of gear efficiency can be used for two main purposes. First, they can be used to convert survey species-size-abundance data into absolute abundance estimates, because they provide the proportionality constant between survey cpua and fish density in the fished area (assuming homogeneity). Given knowledge of sea surface area, the local density can be converted to numbers and summed across wider areas to estimate numbers in regions or populations. Second, efficiency estimates can be used to estimate catch from the spatial distribution of fishing effort. Collectively, estimates of catch efficiency, abundance and catch can be used to assess regional or population status in relation to fishing mortality and biomass reference points.

We employ GAMs to account for differences in fish availability and fishing effort. This use of statistical modelling has been employed by others to estimate catch ratios (e.g. Casey and Myers, 1998; Benoît and Swain, 2003; Heino et al., 2011), but we take the method one step further by rescaling catch ratios to obtain estimates of absolute gear efficiency.

Fraser et al. (2007) used catch ratios between survey gears to derive gear efficiencies for the GOV trawl used in the IBTS. Their results agree closely with our estimates for the GOV. In particular, their analysis showed very low gear efficiencies for small gobies and dragonets, and large efficiencies for gadoids and grey gurnard. They also showed that gear efficiencies of flatfishes varied markedly between species, with high GOV efficiency for dab and very low efficiencies for similarly sized plaice and small flatfish species such as scald fish, solenette and thickback sole. Both our studies found the GOV efficiency for plaice to be <0.1 in the North Sea.

We attempted to isolate the efficiency of gears from overall catchability by using GAMs to account for spatial and temporal patterns in the density of fish available. By including a term for location and date we account for the horizontal availability of fish but ignore the vertical component, so our efficiencies give the probability that fish located within a trawled area will be captured regardless of their position in the water column relative to the trawl. As trawls fish at depths to target a particular component of the fish community, differences in vertical availability are expected to be small in comparison to the horizontal availability of fish across the North Sea. However, an element of vertical availability may feature in our efficiency estimates owing to changes in factors such as headline height and diel, tidally related and other vertical movements of some species.

Our method uses log (swept area) as a model offset to convert from catch numbers to cpua, taking the wingspread of otter trawls as the effective path-width. However, the doors, sweeps and sediment clouds of an otter trawl may herd some species into the path of the net, thereby extending the effective trawl path-width beyond that of the wing spread (Ramm and Xiao, 1995). An alternative estimate of cpua can be obtained by taking the door spread of the trawl as the effective path-width; however, both approaches generally result in biased estimates (Ramm and Xiao, 1995). Wingspread cpua estimates are considered to be the appropriate choice for most fish species, although a few roundfish species are believed to be susceptible to herding, and in this case cpua estimates based on the door spread may be more appropriate (e.g. Fraser et al., 2007; Piet et al 2009). For simplicity, and in the absence of knowledge on the herding of non-target species, we used wingspread cpua estimates for all fish species. However, wingspread-calculated cpuas could account for gear efficiencies >1, as evident in our study when multipliers >1 were obtained for plaice and cod (Walsh, 1996; Winger et al., 2004; Table 3).
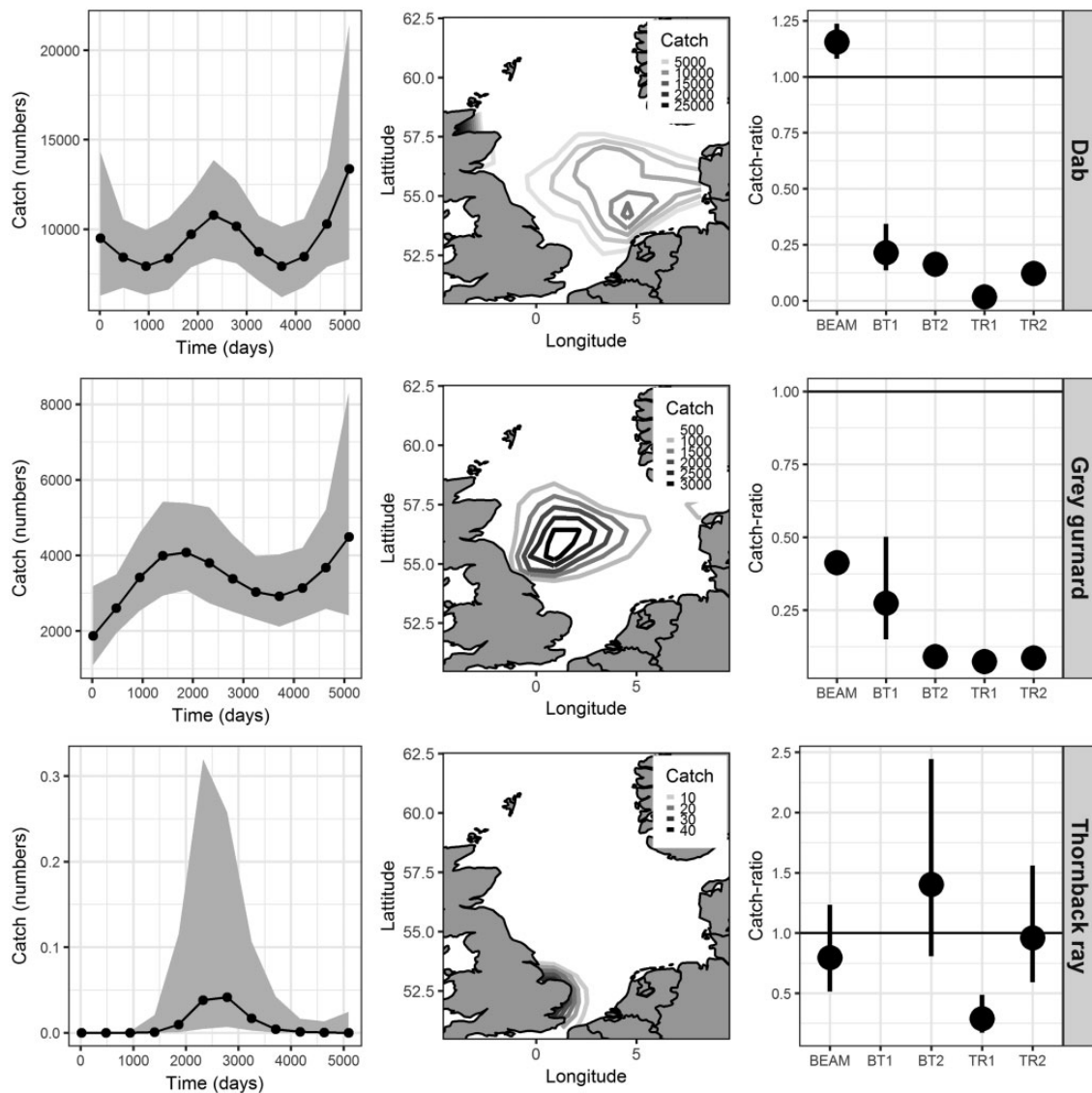
Figure 2. Examples of GAM output for three species in the North Sea: dab (15cm), grey gurnard (20cm) and thornback ray (35cm) showing (left panels) temporal smooths at a central location, (central panels) spatial smooths at 4000 days (13 December 2012) and (right panels) catch ratios (with 95% confidence intervals) relative to the GOV (horizontal line at ratio value = 1).

Our method was applied to catch-at-length data collected from surveys and a commercial catch and discard monitoring program. Unlike research vessels, which use standardised gears and follow a structured survey design, commercial vessels use a variety of net geometries to suit target species and tend to target areas where they expect to find fish of sizes that best meet market demand. Hence fisher behaviour may affect catch-ratios, especially for commercially valuable species. This would explain the high efficiency of TR1 trawls for cod, for example, since a large catch-ratio between the TR1 and the GOV may result if the TR1 is not fished randomly at local scales. Thus if TR1 efficiency is set to 1 and used to scale the GOV efficiency, the GOV efficiency will be underestimated and result in a higher multiplier when survey data are compared with assessments. This effect was evident when the final GOV efficiency was compared with a direct estimate of GOV efficiency (Supplementary material, Figure S11).

By estimating single catch-ratios per species' length class we make the assumption that gear efficiency is constant across time and space. The commercial gear categories we used (EC, 2008b) are quite broad and include nets that are rigged and fished in many ways. Differences in fishing protocol such as rigging, tow duration and speed will affect efficiency of commercial trawls (Winger *et al.*, 2000; ICES, 2004; Reid *et al.*, 2012) and may violate this assumption. Gears might be resolved into more categories to address these differences, but the specificity that is gained will be countered by a reduction in the number of species that can be included in the analysis due to splitting of the data. Overall, we sought to achieve an appropriate balance between gear resolution and available data, but the methods could readily be applied to more refined gear categories in areas and fisheries where adequate data were available at the selected resolution.

When estimating gear efficiency, we defined seven species-groups on the basis of body shape, behaviour, habitat preferences

Table 3. Efficiency multipliers and mean length-at-age (cm) of the representative assessed species used to determine the multiplier for each species group.

| Group	Species	Age										
		0	1	2	3	4	5	6	7	8	9	10
1	Sole		0.40 (14.5)	0.60 (19.7)	0.52 (22.4)	0.51 (23.7)	0.55 (24.5)	0.61 (25.1)	0.77 (26.0)	0.81 (25.6)	0.94 (27.6)	0.47 (26.8)
2	Cod		0.11 (22.8)	0.73 (38.1)	1.38 (54.5)	1.41 (68.3)	1.22 (77.9)	0.65 (86.2)				
3	Plaice		0.12 (15.6)	0.46 (19.4)	0.71 (22.2)	0.76 (24.8)	0.83 (26.6)	0.88 (27.7)	1.03 (28.2)	1.06 (28.1)	0.95 (29.0)	0.95 (28.9)
4	Cod		0.11 (22.8)	0.73 (38.1)	1.38 (54.5)	1.41 (68.3)	1.22 (77.9)	0.65 (86.2)				
5	Norway pout	0.2 (5.5)	0.36 (10.1)	0.53 (13.7)	0.56 (15.2)	0.4 (15.7)						
6	Herring	0.11 (9.1)	0.41 (12.6)	0.30 (19.5)	0.26 (23.1)	0.22 (24.6)	0.28 (25.2)	0.22 (25.7)	0.22 (26.2)	0.22 (26.8)		
7	Plaice		0.12 (15.6)	0.46 (19.4)	0.71 (22.2)	0.76 (24.8)	0.83 (26.6)	0.88 (27.7)	1.03 (28.2)	1.06 (28.1)	0.95 (29.0)	0.95 (28.9)
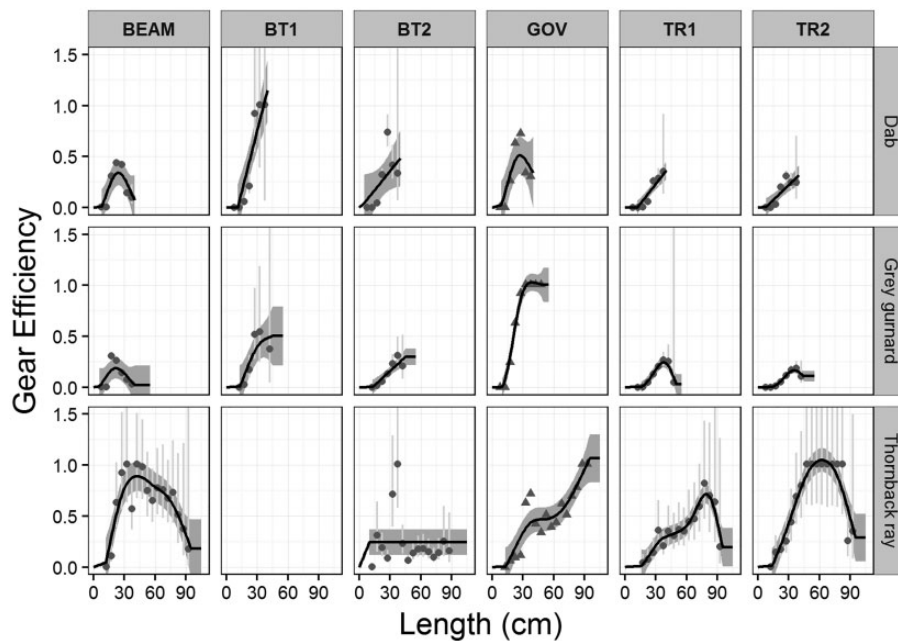
Figure 3. Relationships between gear efficiency and length for three non-target species: dab, grey gurnard and thornback ray. Vertical bars show 95% confidence intervals about estimates of absolute efficiency and shaded regions 95% confidence intervals about the fitted curves. Triangles indicate the reference gear used to derive catch ratios.

and typical position in the water column. Five of the groups were assigned an assessed species from within the group as a representative species, for which multipliers were determined by relating catch numbers estimated from the data to numbers determined from stock assessments. The multiplier of the representative species was then defined as the multiplier for all species within that group. As individual gear efficiencies were derived from group multipliers, any change in abundance estimates in the assessment will affect the estimated gear efficiency of the assessed species and other species in the same group (Fraser *et al.*, 2007). If the efficiency of a gear is constant across time and space, the gear efficiencies we present can be adjusted using new stock assessment data. However, the assumption of constant gear efficiency will necessarily be violated to some extent.

To estimate gear efficiency for all species' length classes, we established relationships between gear efficiency and length. Trawl selection is usually represented by parametric sigmoid or bell-shaped curves, following the principle that larger fish are more likely to be retained in the meshes of the codend (Millar and

Fraser, 1999), but may be better able to avoid the path of the trawl and falling back into the net (Huse *et al.*, 2000). However, gear efficiency can be affected by many factors in addition to gear selection, including fish behaviour, fisher skills and environmental conditions (Zhou *et al.*, 2014). Standard selection curves can be made more flexible to accommodate these factors. For example, Smith and Taylor (2014) developed a peaked logistic-based selection curve, fit using six parameters, that allows asymmetry and non-zero asymptotes. However, because 5 cm length classes are considered, adding this extra complexity would mean that the method could no longer be applied to rarer species with fewer absolute efficiency estimates. Instead, we used non-parametric curves to account for skewness while placing lower requirements on the data. The smoothness of efficiency curves varied with the number of observations: increasing and dome-shaped curves were obtained for most species but more 'wiggly' curves could be obtained for species with a greater number of absolute efficiency estimates. A multiplier of 1.4 was used for all species to inflate the model degrees of freedom in the generalised cross validation score

(Kim and Gu, 2004). This value was adopted for consistency, but could also be determined on a species-by-species basis.

The fitted relationships mostly follow expectations, with (i) a general decrease in gear efficiency with length for survey gears and an increase in gear efficiency with length for commercial gears, (ii) better selection of midwater, pelagic and commercial gadoid species by otter trawls and (iii) better selection of flatfish by beam trawls. A surprising result was the number of species for which large-meshed beam trawl (BT1) relationships could not be derived, particularly for flatfish taken as bycatch. Operating primarily in the central and eastern North Sea, large-meshed beam trawls (BT1) are only used in a small proportion of the study area (Figure 1; Quirijns and Pastoors, 2014) and contribute less fishing effort than the other commercial gears we consider (STECF, 2014). Given that the observer program allocates sampling effort based on the fishing effort exerted (Catchpole *et al.*, 2011), few hauls in our data employed the BT1 gear (< 3% of commercial hauls). A consequence of this lack of sampling is that species that could potentially be caught by the BT1 gear were not observed in the few sampled hauls which took place in close spatial and temporal proximity (Figure 1). Where a BT1 efficiency could not be derived, species were assigned the efficiency of their species-group.

Gear efficiency curves vary within groups for individual species and may display different shapes to those of the species group (Supplementary material, Figures S12–19). We defined species-groups on the basis of body shape, behaviour, habitat preferences and typical position in the water column (Table 2) to allow us to determine gear efficiencies for all species based on assessed species. However, even within groups the gear efficiencies of individual species may vary considerably. Cod, haddock and whiting share a number of morphological similarities but show differences in behaviour towards trawl gears. Main and Sangster (1981) observed that cod stay low when approached by a trawl gear and may escape under the bobbin spacers, haddock rise and sometimes escape over the headline and whiting tend to swim in the middle.

Mean gear efficiency estimates for non-target species are already available for the GOV trawl (Fraser *et al.*, 2007) and are comparable with those we generate with our GAM-based approach. We also report uncertainty associated with our mean efficiency estimates for the GOV gear, as well as reporting efficiency and associated uncertainty for BTS gear and commercial trawl gears accounting for 95% of North Sea fishing effort (STECF, 2014). Our flexible method could also be used to estimate the efficiency of towed gears for non-target species in other regions where assessments provide absolute abundance estimates for target species caught with the same gears. The estimates of efficiency we generate may be used to estimate absolute abundance of non-target species from catch data, as well as fishing mortality, reference points and a range of other metrics needed to support management advice. The estimates may be used directly in the North Sea but are also likely applicable to these species or groups when they are fished with the same gears in similar physical environments (e.g. similar depths, habitat types, water clarity, temperature).

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

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