Fisheries Management and Ecology

Fisheries Management and Ecology, 2013, 20, 377–389

Effective fishing effort indicators and their application to spatial management of mixed demersal fisheries

A. N. TIDD

Cefas, Lowestoft, Suffolk, UK

Abstract Since the Common Fisheries Policy reform in 2002, there have been various proposals for designing effective input-management tools in the context of demersal multispecies and multimétier fisheries to augment quota management. The relationship between fishing mortality and effort exerted by the English beam trawl fleet is investigated for two stocks of North Sea demersal fish, plaice, *Pleuronectes platessa* L., and sole, *Solea solea* (L.). Catchability was adjusted by accounting for targeting by this gear, seasonal and area effects, and individual vessel variation, using results from a generalised linear mixed-effects model (GLMM) that included random effects (in this case, vessel). Descriptors were standardised in relation to distinct submétiers and their impact on both species. Fishing efficiency was calculated as the ratio between relative nominal landings per unit effort derived from the GLMM and survey indices from a standard survey vessel. Fishing efficiency for sole increased (+0.6% annually) and for plaice decreased (−6.2%), likely because of changes in targeting, fuel costs and regulations.

KEYWORDS: catchability, effective effort, effort control, fishing efficiency, GLMM, North Sea flatfish fishery.

Introduction

The management of European mixed fisheries is primarily based on total allowable catches (TACs) along with effort restrictions (days-at-sea), technical measures (gear and/or mesh size regulations, size restrictions) and seasonal closures. The difficulties in managing fish stocks through TACs are widely recognised (Shepherd 2003; Beddington *et al.* 2007). The main issue is that a TAC set to protect one species within a mixed fishery can have an undesired effect on another through increased discarding, or indirectly through foodweb interactions. Hence, a conservation policy cannot achieve its goal through this single management action. For example, a TAC for one species in a fishery may be exhausted earlier in the year than for another species taken by the same fleet/fishery (Vinther *et al.* 2004). The fleet could then continue to fish the same grounds until it landed the TAC remaining for each target species, but any catch of a species for which the TACs were exhausted would have to be discarded. Discarding species that almost certainly die on return to the sea or the illegal retention of the catch leads to socially undesirable results (Copes 1986). Since the Common Fisheries Policy (CFP) was initially revised in 1992, fishing effort management schemes have had an increasing role as tools to control fishing mortality. Effort management differs from TACs in that controls on effort manage the input rather than the outputs specified by a TAC, although they both aim to limit fishing mortality.

In fisheries science, fishing effort (E) is an essential parameter in the assessment of fish stocks and their effective management. It is linked to fishing mortality (F) via the catchability (q) at age of a stock, a term that generally means the extent to which the stock is susceptible to fishing and that would be captured by one unit of effort. Catchability is therefore as important to managers as effort in assessing fish stocks and ultimately in supporting effective management. The relationship is assumed to be linear and takes the form $F = qE$. Fishing effort, however, is difficult to quantify because the sizes and types of vessels and gears differ. It is usually approximated by a metric of capacity, such as gross tonnage or engine power, with a measure of activity (e.g. days-at-sea or hours fished), and is therefore an aggregated measure of fisher behaviour in locating the greatest densities of marketable fish (Rijnsdorp *et al.* 2006). Nevertheless, capacity has not always decreased

*Correspondence: A. N. Tidd: Cefas, Pakefield Road, Lowestoft, Suffolk NR33 0HT, UK (e-mail: alex.tidd@cefas.co.uk)

doi: 10.1111/fme.12021

at the same rate as stocks (Cunningham & Gréboval 2001), and as resources are depleted, fishers tend to redistribute their fishing effort across other fisheries, implement new technologies such as advanced fish-finding devices (Branch *et al.* 2006), or participate in illegal, unreported and unregulated (IUU) fishing (Agnew *et al.* 2009). In addition, vessels and/or gears may be modified to circumvent regulations and/or to increase effective fishing power, in an attempt to continue harvesting at the most profitable level (Gréboval 1988).

The efficiency of fishing vessels and hence catchability tends to increase over time because of factors such as fishing technology improvements. This increase, known generally as technological creep, can be quantified in relation to fishing mortality with constant nominal effort (E_n) and intensified effective effort (E_e). These relationships are important to fishery managers because they are crucial in reducing fishing mortality through effort control, and ignoring them could prove meaningless in limiting fishing mortality (Pauly *et al.* 2002). Shepherd (2003) suggested that for a given amount of effort exerted, and because of variations in vessels and their activity, different effects on stocks can be generated. Therefore, it would be necessary to set effort limits at the individual level based on area fished and gear used. Standardised fishing effort has been interpreted in the literature, however, in different ways, and there is some contention within the fisheries scientific community as to what it actually means, and also as to how any problem should be addressed. Many authors have tackled it using statistical regression models (Maunder & Punt 2004), where some dependent variable, for example, catch per unit effort (cpue), is modelled as a function of plausible explanatory factors such as seasonal, temporal and gear characteristics (Hilborn & Walters 1992; Weninger & McConnell 2000; Hinton & Maunder 2003; Mahévas *et al.* 2004; Piet & Jennings 2005; Bishop 2006; Marchal 2008). The parameters from such models are then used to estimate the value of the variable in question for any combination of seasonal, temporal and technical (e.g. gear) factors. Since the 2002 CFP reform, there have been various management and recovery plans, as well as some difficulties in designing relevant, efficient and effective management tools in the context of multispecies, multimétier fisheries. Hence, there is an increasing role for input management as part of ongoing CFP reform.

The aim of this study was to evaluate the relationship between fishing mortality and nominal effort applied on two North Sea demersal stocks, plaice, *Pleuronectes platessa* L., and sole, *Solea solea* (L.), caught by the English beam trawl fleet, using an adaptation of the commonly used general linear model (GLM; Nelder & Wedderburn 1972). Effort indicators for UK fleet capacity based on vessel capacity units (VCUs[1]) determined by vessel size and engine power, and hours fished were used rather than the more traditional metrics (e.g. kW and days-at-sea). Methods of standardising such descriptors in relation to submétiers and their impact on both species are suggested, allowing for potential changes and strategies in the fishery to be evaluated. The basis for the approach is to resolve potential conflicting spatial management advice for different species that can be taken in the same fishery, and which could be applied at an individual level, as suggested by Shepherd (2003). Multispecies fisheries are difficult to manage, so advice at the fleet or fishery level may be more effective than trying to balance and integrate single-species advice for a range of stocks (Vinther *et al.* 2004). This means that altering effort controls or spatial regulations for one stock can have implications on others and the wider ecosystem.

Methods

English beam trawl vessels in the North Sea have traditionally caught plaice in a directed fishery using 120-mm mesh north of 56°N, and in a mixed fishery with sole, using 80-mm mesh, in the southern North Sea. In 2005, international landings of North Sea plaice amounted to 55 700 t, compared with a peak of 170 000 t in 1989. Reported international landings of plaice from the North Sea were dominated by the Netherlands (40%), followed by the UK (23%) and Denmark (20%), with Belgium, Germany, France and other countries reporting the remaining 17% (ICES 2007). In the English fishery, the high value of sole makes it one of the most important species targeted by inshore vessels operating trawls and fixed nets. The fishery is conducted mainly from March to October, but sole are also taken as a target species by offshore beam trawlers, otter trawlers and gillnetters. The English North Sea beam trawl fleet until 2003 operated mainly out of east coast English ports, typically spending on average 250 d at sea in trips lasting about 6 d (Hutton *et al.* 2004). Since 2002/2003 and the transfer of ownership to the Netherlands, however, skippers have generally targeted sole because of its greater commercial value and short distance from their Dutch home port.

Data

Individual trip data for the commercial beam trawlers were collated for the years 1997–2007 and examined by

[1] A VCU is a unit used by the UK as part of fleet capacity management (see UK Fisheries Department 1988).

area. These areas were based on International Bottom Trawl Surveys (IBTS) and in particular the Netherlands beam trawl survey (BTS), which stratifies its sampling of sole and plaice by Roundfish areas (Fig. 1; ICES 2009). Roundfish areas 1 and 3 were excluded from the study because English beam trawlers generally do not fish there. The data collected for each vessel and trip included species landed, hours fished, landed weight (kg) per ICES statistical rectangle, month, year and total value of the catch by species. Within the EU, it is a requirement for vessels >10 m long to submit logbooks, but the database contained a subset of catch from <10 m vessels that historically reported their catches. Fleets were defined to align with those in the data collection regulation (DCR) of the European Commission (EC 2000). A method was developed independently (see EC 2006a), preceding the current data collection framework (DCF; EC 2008) that defines the beam trawl fleet on the basis of its use of a beam trawl for >50% of a fishing trip. The fleet activity, or métier, is determined by a fisher's tactic at a trip level, and is defined on the basis of the mix of target species. In other words, métiers are characterised on the basis of the outcome of a trip and defined by gear, fishing grounds and composition of landings. The compositions of landings were calculated as a proportion of the total value of the catch, thus removing the differences in catch rate attributable to vessel capacity. Catch proportions were based on economic value rather than weight, reflecting the notion that fishers are profit maximisers, so valuable species received more importance in the analysis. In this study, the beam trawl métier that primarily targets crustaceans (brown shrimp) was omitted, and a single demersal métier was defined (demersal beam trawl) and used for analysis. The fleet targets the main commercial flatfish stocks (plaice and sole) in the North Sea.

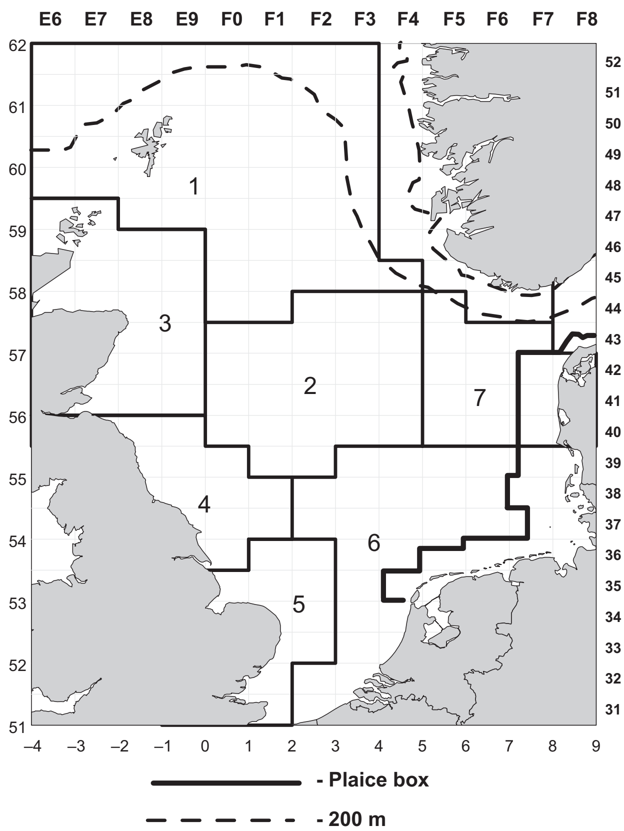

Figure 1. Map of the North Sea showing ICES statistical rectangles and roundfish areas (1–7), with the plaice box indicated by the heavier dark line (closed to beam trawlers of hp >300 for the whole year since 1994).

Exploratory analysis and covariates

Vessel landings per unit effort (lpue) were calculated from logbook-recorded landings as kg per h fished per vessel per trip per area (ICES statistical rectangle; Fig. 1). Although haul-by-haul data are preferred for such analyses, logbook declarations are by day and by ICES statistical rectangle per trip. The underlying statistical distribution generating the data was also hypothesised to be of the form of a gamma distribution, but after examining the data, a lognormal distribution was investigated and normality tested using Q–Q plots. In keeping with other studies (e.g. Butterworth 1996; Ortiz *et al.* 2000; Ortiz & Arocha 2004), zero lpue values were addressed by the addition of a positive constant of 1, because the logarithm of 1 is 0 (Ortiz & Arocha 2004).

Vessel capacity units, that is, overall length $\times$ breadth of vessel (both in m) + engine power (kW) $\times$ 0.45, were chosen simply because this metric is used in policy and combines characteristics recorded in the UK fleet register. Unfortunately, other potentially relevant covariates, such as the electronics used (e.g. global positioning systems, GPS, plotter software, fish finding equipment, seabed mapping and navigation systems), skipper and crew experience in the fishery, and specific technical characteristics of the gear, are not available from logbooks or fleet registers. These can be obtained only by face-to-face interviews with the skipper, and would also change over time. Year was included as a factor to capture temporal changes in technology or fluctuations in stock abundance. Month and area (ICES rectangle) were included to account for strategic/tactical effects (e.g. responding to seasonal changes in stock abundance). Vessel effect was considered an important factor and included, because it could be an indication of skipper/crew experience and gear characteristics (Mahévas *et al.* 2011).

The model

Generalised linear mixed-effects models (GLMMs) are used widely in ecological research (Bolker *et al.* 2009), but less so in fisheries (Venables & Dichmont 2004a). Nevertheless, the applications of GLMMs are beginning to be explored using catch and effort data (Bishop *et al.* 2004; Helser *et al.* 2004; Baum & Blanchard 2010; Tascheri *et al.* 2010). A GLMM is a generalisation of a GLM (Nelder & Wedderburn 1972), such that the data are permitted to exhibit correlation and non-constant variance (Diggle *et al.* 2002; Venables & Dichmont 2004b). A GLMM therefore provides the flexibility of modelling not only the statistical means of data (as in the standard linear model) but also their variance and covariance. The term mixed model refers to the use of both fixed and random effects in the same analysis. The model is described formally as:

$$\eta_i = \sum_{a=1}^{f} \beta_a \chi_{ia} + \sum_{b=1}^{r} Z_{ib} \upsilon_{ib}, \tag{1}$$

where $\beta_a \chi_{ia}$ are the fixed effects as descriptors of lpue (η_i), and $Z_{ib}\upsilon_{ib}$ are the random effects made up of Zib, the levels of the random effects, and υ_{ib} is assumed to be distributed normally.

For comparison with the GLMM analyses, a basic GLM with temporal and vessel characteristic fixed effects was constructed as:

$$\ln(lpue) \sim vcu + year + month + area + month \times year + month \times area. \tag{2}$$

Variables were selected initially based on their importance as reported in a pan-European study by Mahévas *et al.* (2011) and their availability from logbooks: final selection was based on their statistical significance at a level of α of 0.05, following stepwise backward selection.

Two other alternative models with the same fixed effects as (2) but with different random effects assumptions were compared using GLMM methodology (1). Alternative regressors of fishing power were considered and for these analyses, vessel tonnage was replaced with VCU, which is highly correlated with the other technical characteristics of the vessel, and *vessel* was not considered a fixed effect but rather treated as a random effect. Earlier studies explored the use of random effects of vessel and vessel–year interactions when standardising catch and effort data in examining fishing power (Bishop *et al.* 2004; Helser *et al.* 2004). Based on those studies, the same method was applied in the choice of the variable *vessel* to account for between-vessel variation, and *vessel and year* to account for vessel variation over time, to capture increase or decrease in fishing power and skipper changes. The model was developed to capture the variation within vessels and between times, to account for potential technical changes in fishing power over the study period. For example, older vessels in earlier years should have lower fishing power than vessels that joined the fishery later. Residual plots were plotted against predicted values and tested for normality using Q–Q plots. The GLMMs were then compared by inspecting the Akaike information criteria (AIC; Akaike 1974). All model analysis was implemented by PROC GLIMMIX (SAS Institute Inc. 2006).

Relationship between fishing effort and fishing mortality

The link between F and nominal E can be characterised by the catchability coefficient q (which relates to biomass abundance, and is the fraction of fish caught by a defined unit of effort, see above); catchability also links population biomass abundance N to cpue as cpue = qN.

Following Mahévas *et al.* (2004, 2011), it was assumed that lpue can be represented as

$$lpue = \frac{landings}{fishingtime} = aPEN, \tag{3}$$

where a represents the accessibility coefficient of the target population, and P the fishing power of the vessel targeting population N applying nominal fishing effort E (in this case hours fished represented by E_n). The product of aP is the catchability. The different factors characterising fishing effort estimated from the model can be used to calculate effective fishing effort E_e by adjusting nominal effort. The relationships between fishing mortality were investigated by plotting log-transformed partial ln(F) against log *effort*, ln(E_n) and ln(E_e) for all trips in the time period, and the r^2 values compared. Relative nominal and adjusted lpue and effort were calculated based on annual totals and averages of the totals for the period of the study. Fishing efficiency was calculated based on a method used by Marchal *et al.* (2002) and Engelhard (2008), the ratio of relative nominal lpue and survey stock assessment indices from a standard survey vessel that was used consistently throughout the time period of study (ICES 2007) for each species by comparing start and end estimates weighted by the number of years to give average weighted increase or decrease.

Estimates of fishing mortality

Total international landings and estimated values of fishing mortality were obtained from ICES annual stock assessments (ICES 2007) for North Sea sole and plaice. Partial fishing mortalities were calculated as

$$F_{ysvta} = F_{ys} \frac{\sum l_{ysvta}}{\sum l_{ys}}. \quad (4)$$

The subscripts l, y, s, v, t and a refer to landings, year, stock, vessel, trip and area, so F_{ys} is the total fishing mortality by year and stock (or mean F over selective ages 2−6 (for both stocks), $\sum l_{ys}$ the total international landed weight in kg per year and stock, $\sum l_{ysvta}$ the total landed weight in kg per year, stock, vessel, trip and area, and F_{ysvta} the partial fishing mortality by year, stock, vessel, trip and area.

Investigation of submétiers within a fleet using multivariate techniques

The aim here was to characterise the tactics of a trip based on the effective effort on sole and plaice, to give an indication of the operational activities of the vessels (i.e. grouping the vessels into similar subgroups linked to area, season, capacity and ultimately related to approximate fishing mortality) and to use the information as a tool or indicator for managing the mixed fishery. For this study, the Ward minimum variance clustering method was used, in which the distance between two clusters was the ANOVA sum of squares between two clusters added up over all variables (SAS Institute Inc. 1996). This method was preferred because it produces tighter clusters (Gauch 1982). Ward's minimum variance method tends to join clusters with few observations, and is strongly biased towards producing clusters with roughly the same number of observations. A hierarchical agglomerative clustering (HAC) analysis was used to define subfleets.

Results

Convergence was achieved for all GLMM and GLM models (Table 1). The model containing the random effects to account for between-vessel variation and vessel variation between years and vessel variation over time had the lowest AIC and was considered the best model for both species (Pinheiro & Bates 2000). The plots of residuals against predicted lpue did not show trends and the Q−Q plots followed the reference line, suggesting that the distribution was close to normal and that the correct error models were selected. Furthermore, plots of subject against fitted indicated that all the model outputs tracked the data well, with all values of $r^2 > 0.56$ (Table 1).

Using parameter estimates from the descriptors of the GLMM to describe lpue, fishing effort was adjusted. The r^2 values for the log of partial F vs effort relationships (nominal and adjusted) for sole and plaice increased from 0.11 to 0.74 and 0.51 to 0.89, respectively, when effort was adjusted by the parameter estimates of the model (Fig. 2). The implications of this are that there has been an improvement in the definition and modelling of metrics (effort, capacity and others) that defined the relationship between effort and capacity and F.

Fishing efficiency and year effects

Trends in effort (nominal and adjusted) and lpue (nominal and adjusted) over the study period (1997–2007) for

Table 1. Diagnostic statistics for the best models explaining plaice and sole lpue as a function of vessel and accessibility (year, month, area) characteristics. The best GLM model (i.e. without random effects) is shown as the basic model (models 1 and 4). GLMMs 2 and 5 have fixed effects equivalent to the basic model but also include the random effects of individual vessels. GLMMs 3 and 6 include the random effects of vessel*year interactions (interpreted as 'technological creep').

Model		AIC	ΔAIC	Subject against fitted (r^2)	d.f.
	Plaice				
	GLM without random effects, and including main effects				
1	*vcu + year + month + area + month × year + month × area*	49 141.28	9979.48	0.74	20 263
	GLMM, including random effects				
2	*Basic + vessel*	42 483.61	3322.09	0.80	20 124
3	*Basic + vessel + vessel × year*	39 161.52	0	0.84	19 701
	Sole				
	GLM without random effects, and including main effects				
4	*vcu + year + month + area + month × year + month × area*	64 029.54	5510.08	0.57	20 263
	GLMM, including random effects				
5	*Basic + vessel*	60 032.64	1513.18	0.62	20 124
6	*Basic + vessel + vessel × year*	58 519.46	0	0.66	19 701

AIC, Akaike information criterion.

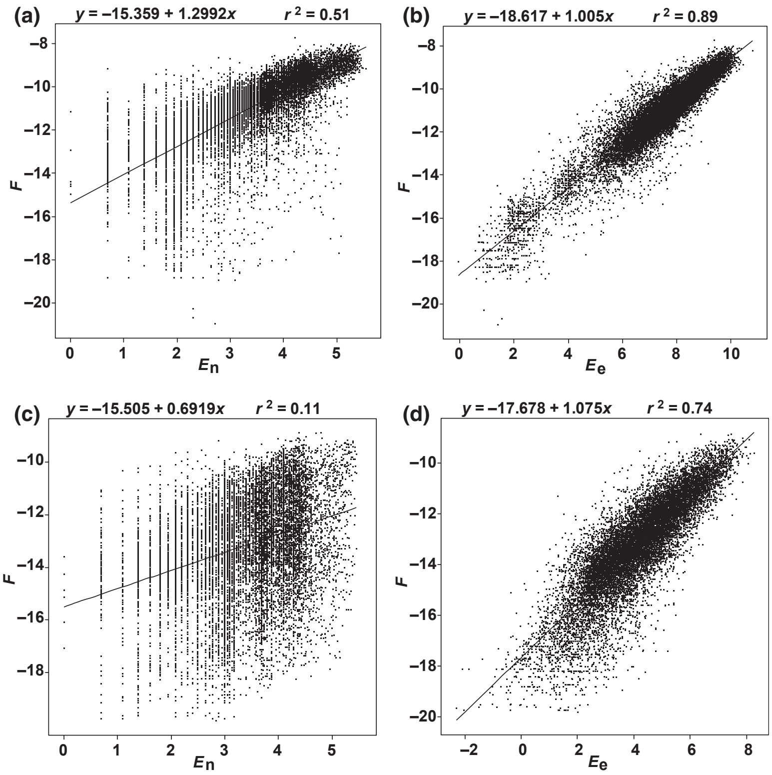

Figure 2. Relationships between fishing mortality (F) and [(a) and (c)] nominal effort (E_n) and [(b) and (d)] adjusted effort (E_e) for (left panels) plaice and (right panels) sole.

the various stock/fleet combinations are displayed on Figure 3. For both stocks, there was a downward trend over time in both nominal and adjusted effort, but this trend appears to have stabilised for the final 3 years of the analysis. In terms of lpue, there was no trend for plaice, but there was an increase for sole over the final 5 years of the study period. Analysis of the percentage change in fishing efficiency resulted in an annual 6.2% decrease for plaice and a 0.6% increase for sole. These results coincided with the transfer of ownership to the Netherlands, where skippers generally target sole because of its greater commercial value and availability relatively close to port in the southern North Sea, vessels generally operating in Roundfish area 6 (Fig. 1).

Cluster analysis

The results of the Cluster Analysis pseudo F and cubic clustering criterion (ccc; SAS Institute Inc. 1983; not shown) revealed local peaks at three clusters, reinforced by a local low t^2 and a levelling of R^2 for these clusters, indicating three distinct submétiers (Fig. 4). Exploratory analyses (Figs 5–7) showed interesting spatial and temporal patterns. Clusters 1 and 2, although close spatially (Fig. 5), were distinguished seasonally (Fig. 6) in terms of a decrease in effective effort on sole during the second quarter of the year for cluster 1. Cluster 3 was distinct, being mainly a sole fishery just off the English coast fished mainly by inshore vessels of smaller capacity (VCU).

Application of the analyses

As a demonstration of utility of the analysis in terms of management indicators, the effects of reducing fishing mortality on both stocks for a given reduction in mortality on one stock were estimated. Taking into account the relationships between effective effort and fishing mortality for each submétier/cluster and the trends for each cluster over time, for each gear grouping and area, a simple management approach is presented to demonstrate application of the approach. Using the values produced from the cluster analysis, Figures 6 and 7 show where the main effort is in terms of trip numbers and effective effort by area and season. For example, if a manager wishes to reduce fishing mortality on plaice by 20% in the first quarter of the year in Roundfish area 6 (or in rectangles in this area) for cluster 2 (Fig. 7a) and vessels with a

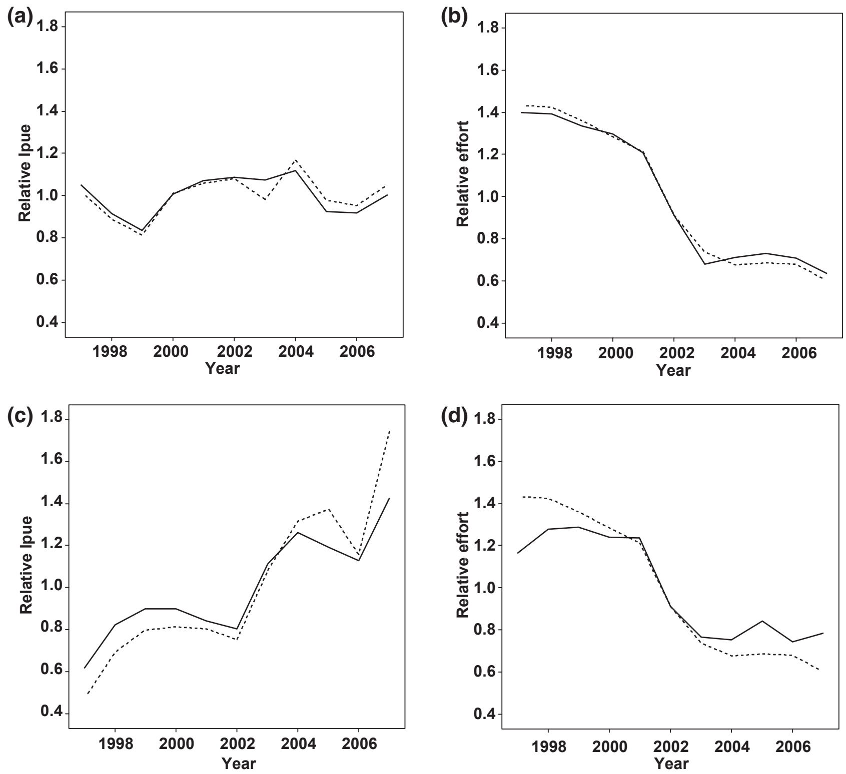

Figure 3. Relative [(a) and (c)] landings per unit effort, lpue, and [(b) and (d)] relative effort for (top panels) plaice and (bottom panels) sole for the English beam trawl fishery in the North Sea (1997–2007), with data for both nominal effort (E_n) (dashed line) and adjusted effort (E_e) (solid line) indicated.

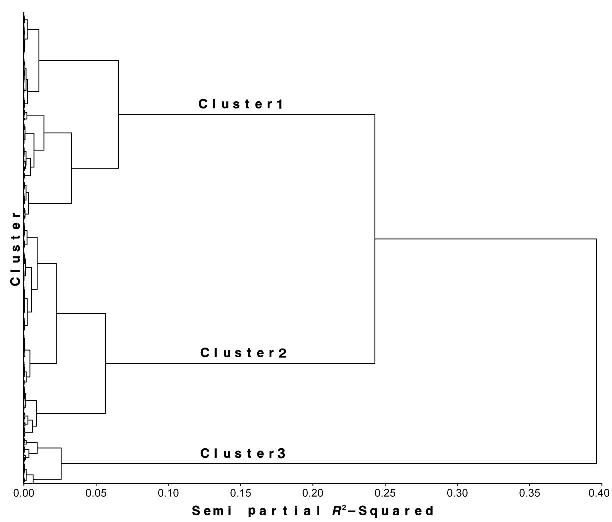

Figure 4. Dendrogram of the beam trawl fishing trips in the North Sea, based on effective effort profiles for sole and plaice.

VCU of 800−1099 (Fig. 7b), the effective indicators provide a platform to control fishing mortality by reducing the hours fished. An example is described below.

Step 1 Taking the example from above, in 2007 there were ~120 trips (Fig. 7) exerting an average effective effort of 8 (Fig. 6; plaice effective effort). A fishing efficiency decrease of 6.2% is applied to estimate the effective effort, which results in a new effective effort of 7.94 (e.g. exp (8) × 93.8%, then back-transformed).

Step 2 Applying the effective effort from Step 1 (Fig. 2b, using the equation from the plots) results in a fishing mortality on plaice of −10.641 in total, equating to exp (−10.641) × 120 trips) and an estimate of F of 0.002869.

Step 3 A 20% reduction results in an F-value of 0.002295. The average per trip log-transformed gives an F-value of −0.864, which results in an effective effort of 7.71 (Fig. 2b) and a nominal effort of 3.46 (Fig. 2a). The nominal effort back-transformed approximates to 32 h per trip, an overall reduction of 6 nominal hours fishing per trip per vessel from the original calculated nominal effort of 38 h based on −10.641 fishing mortality (Fig. 2a).

Step 4 To provide an indication of the effect on sole for a 20% reduction in plaice, a ratio of the start and end estimates of effective effort of plaice as calculated in the steps

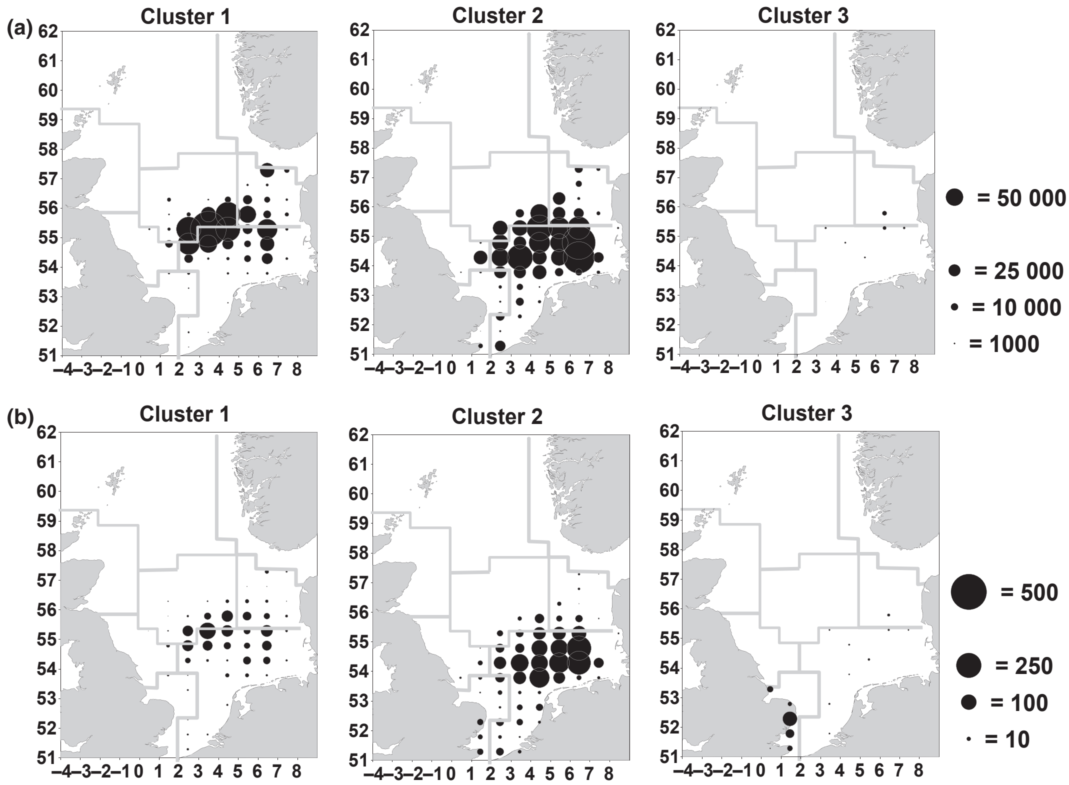

Figure 5. Total effective effort of (a) plaice and (b) sole by cluster for 2007.

above (7.71/7.94) was applied to the mean effective effort on sole (Fig. 6; sole effective effort 5.5, including 0.6% fishing efficiency increase), which was estimated at 5.73 and the associated F calculated to be -11.52 (Fig. 2d). Applying the ratio, the resulting effective effort was 5.57 and the revised F -11.69, giving a total reduction of 15.8% in sole mortality and a total reduction of 720 h fishing based on a 6 h reduction $\times$ 120 trips.

Discussion

The analysis has provided an understanding of the relationships between some of the parameters that allow linkages to be drawn between capacity, effort and fishing mortality and of their use as indicators for spatial and temporal management of the North Sea flatfish beam trawl fishery. It also takes account of changes in capacity and fishing power. Limiting fishing through effort controls via spatial management requires an understanding of likely fisher response, and also an ability to predict the choice of fishing area or fishing activity (Vermard *et al.* 2008; Tidd *et al.* 2012). Here, no attempt was made to predict the choice of fishing ground, but on the basis of fisheries seasonality, Tidd *et al.* (2012) provided a simplistic ecosystem approach (FAO 2003) to manage a fleet's activity in a particular area (Daan 2005), targeting sole and plaice. Bycatch species were not included in the model because of the lack of estimates of fishing mortality, nor were benthic habitats of conservation interest included.

A GLMM that included random effects (in this case, vessel) was applied to lpue as the dependent variable to explain the variance attributable to targeting by the gear, changes in efficiency, capacity, seasonal and area effects. This method was selected over the more traditional GLM because of the unbalanced data set, that is, not all vessels operated throughout the study period. As such, including the vessel as a random effect takes account of inter-vessel variation and variation between individual vessels over time; ignoring it could produce negatively biased lpue estimates. The model parameter estimates for sole and plaice were adjusted with nominal effort and fitted against F. Both adjustments resulted in improved relationships relative to F vs nominal effort. Relative adjusted effort over the study period declined initially for both species, but stabilised towards the end of the study period, whereas relative adjusted lpue improved slightly for sole and increased the fishing efficiency for this species. Cluster analysis of individual trips, based on estimates of effective effort for sole and plaice, revealed three main submétiers within the fleet, which then made it possible to estimate spatially the effect on

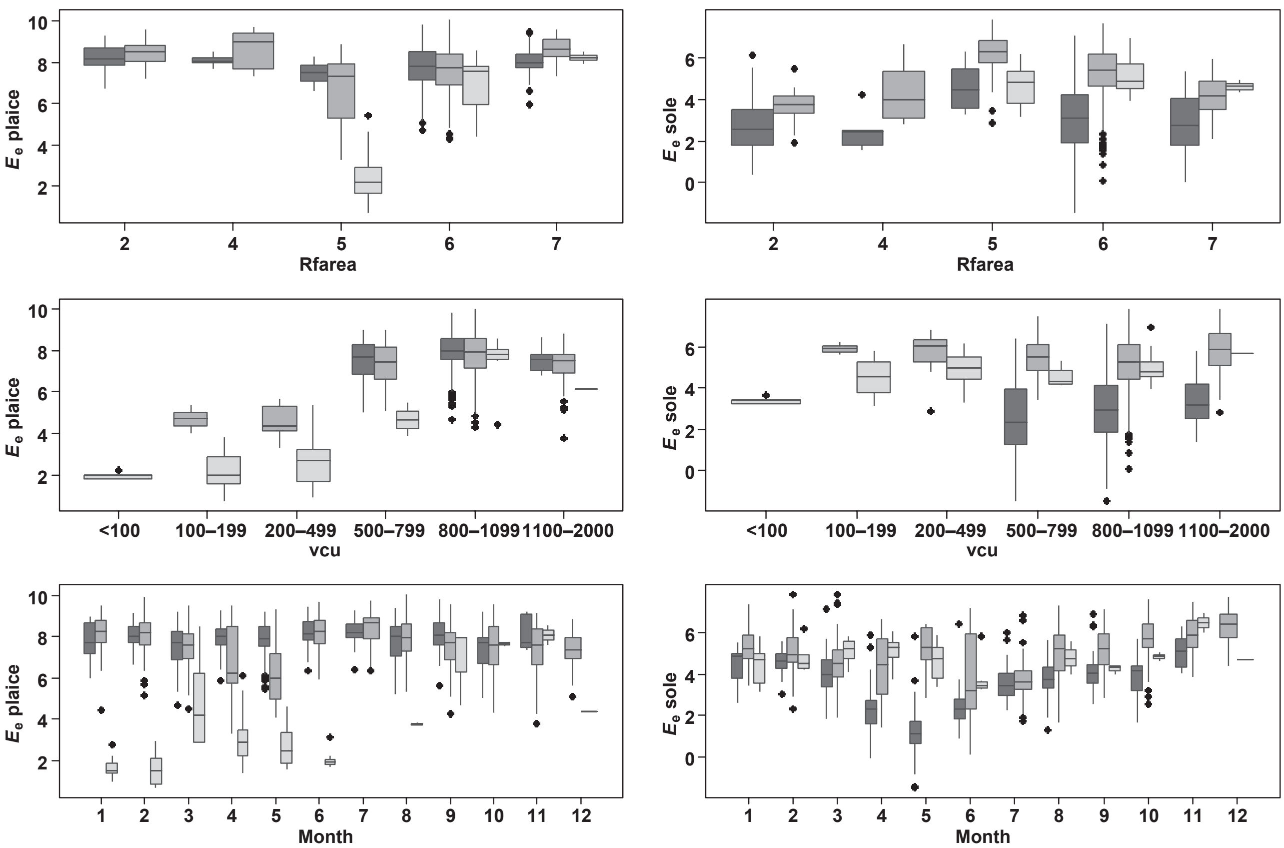

Figure 6. Effective effort indicators. Box and whisker plots of clusters vs the different covariates (roundfish area, VCU and month) for plaice (left panels) and sole (right panels) in 2007. The horizontal line represents the mean, the box the 25th−75th percentiles, the whiskers the ranges of data, and the solid diamonds outliers, with Roundfish areas (Rfarea) displayed because they demonstrate the approach more clearly than a series of ICES rectangles. (Cluster 1 = dark, Cluster 2 = medium dark, Cluster 3 = light).

one stock of applying an effort or fishing mortality limit (including fishing efficiency).

The model relied on estimates of F from ICES working groups. If the F estimate was biased there would be variances in the F~E_e relationship. Landings are not always a direct proxy for fishing mortality, because of discarding, however, and discarding was not taken into account in these analyses because the information was not available for all fleet segments/submétiers. The quality of other data sources (e.g. VCUs derived from the fleet register), and the collection and databases of logbook information, cannot be assessed. The results from the F-reduction exercise underscore the difficulties in controlling fishing effort when managing a mixed fishery, because the nominal effort vs mortality relationship for sole had a poor fit (Fig. 2c). The analysis relied heavily on the plaice fit (Fig. 2a), which provided a better indication of nominal effort exerted at a trip level. The effective effort indicators were based on means (Fig. 6), although they showed the relative uncertainty or spread of the data associated with respect to each factor. However, such a spread of data for each factor is not uncommon, because fisher behaviour varies and leads to different values of effective effort. Managers applying effort limitation need to be aware of the variability in catchability by fishers in the same fishery acting on the same stock group.

The seasonal nature of the fishery was evident from the analyses (Fig. 7). There was typically more effort at the start and end of the year in Roundfish area 6 for cluster 2, reflecting targeting of plaice then and corresponding to the seasonal migration of the fish from the central North Sea (Roundfish area 2) to the southern spawning grounds (Roundfish area 6; De Veen 1978; Rijnsdorp & Pastoors 1995; Hunter *et al.* 2003), and greater effort in Roundfish area 5 in late spring and summer, possibly reflecting beam trawling for sole on their spawning grounds near the English east coast (Cluster 3; De Veen 1976). Cluster 1 (in contrast to Cluster 2) was characterised by more effort farther north in Roundfish area 2 throughout summer, but this was not as prominent at the start or end of the year. The results support the findings of earlier studies of clear seasonal trends in beam trawl effort redistribution throughout the study period (Tidd *et al.* 2012).

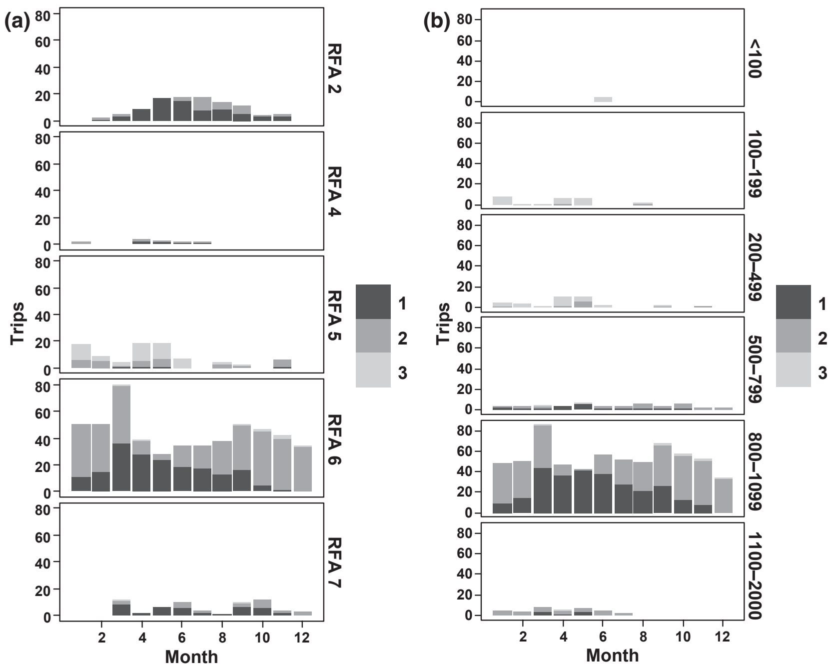

Figure 7. Number of trips by (a) Roundfish area (RFA) and (b) VCU by cluster (1−3) and month for 2007.

One of the main assumptions here was that fishing VCU was a proxy for capacity, the rationale being that the unit is the basis of vessel-reduction programmes (Multi Annual Guidance Programmes; UK Fisheries Department 1988) in the UK. Vessel landing rates, that is, nominal lpue values, were calculated as catch in kg per h fishing per vessel per trip per area. The importance of making management decisions on effort measured in hours, in theory, may provide a less crude measure that relates closely to actual fishing activity rather than the current days-at-sea restrictions applied to North Sea fleets. However, the current regulations are expressed in days-at-sea to simplify the process in terms of enforcement. Irrespective of potential changes in fishing tactics to maximise number of hours fished, increases in efficiency are evident for one stock (sole), whereas decreases in efficiency for plaice could indicate increased targeting of sole (Fig. 3). More importantly, the slope of the regression in each case increased (see Fig. 2). In practice, this implies that management that considers several factors (capacity, seasonal and area effects) that contribute to effective effort should be more effective in reducing fishing mortality than management based purely on nominal effort. The policy implications are such that adjusting effort such as days-at-sea (or h-at-sea) by capacity (and taking into account month and area effects) should result in greater than proportional decreases in fishing mortality. How viable it would be to adjust for such an approach through regulation and enforcement requires more study. Changes in catchability that arise when applying additional nominal effort or fishing efficiency are important to fisheries scientists, to monitor changes in F, and likewise, for a given F, the effective effort will be influenced by fishing efficiency and the nominal effort will need to be adjusted appropriately.

A key finding from the study was the switch in targeting and the changed fishing efficiency, an estimated 6.2% decrease in plaice and an estimated 0.6% increase in sole annually for averages calculated over the 11-year study period. The decrease in plaice efficiency is of interest because the concept of negative creep is becoming more evident especially as fuel prices rise. Increasing fuel costs in beam trawling (Abernethy *et al.* 2010; Tidd *et al.* 2011) may well have influenced the distribution of the fleet in the southern North Sea, with less steaming time to ports in the Netherlands reducing operating costs to counteract fuel price increases. English beam trawlers generally target both plaice and sole, but in recent years, because of the shrinking fleet size and transfer of ownership to the Netherlands, sole has generally been targeted because of its greater commercial value and short distance from port in the southern North Sea, also perhaps contributing to the increase in efficiency and the decrease in catches of species targeted previously (Marchal *et al.* 2003; Engelhard 2008). Measures in 2007 to protect juvenile cod, *Gadus morhua* L., as part of the cod recovery plan were imposed on certain beam trawl gears; an

8% reduction in effort from 2006 was enforced, and this could have also contributed to the fleet fishing closer to port and the switch in target species (EC 2006b,c).

Limiting and reducing the time a vessel spends fishing is possible in theory, but out of sight of regulatory enforcement it used to be difficult to control. With the application of Vessel Monitoring Systems (VMS), however, it has become possible for regulatory authorities to monitor the activities and locations of commercial fishing vessels better, although there remain problems in identifying activity and there are anyway limitations in VMS data use (e.g. the time between satellite pings that monitor the vessels; data being collected only on vessels ≥ 15 m long within the UK; accurate matches with landings data by trip and ICES rectangle; and for scientific studies, confidentiality), which is why days-at-sea effort restrictions have been preferred in EU waters.

A spatial means of effort control to reduce fishing mortality and discards on cod and to encourage compliance introduced by the Scottish Government in 2008 after consultation with stakeholders was that of real time closures (RTCs). Fishers were rewarded with extra days-at-sea for avoiding areas where the lpue of cod was high. Currently, the threshold for enforcing a RTC is 40 cod per hour fished; one catch exceeding this threshold triggers a closure. Early studies by Needle and Catarino (2011) using VMS data showed that vessels tended to move away from RTCs, but also that vessels returned to these areas shortly after the closure ended. Overall, the conclusion on RTCs was that mortality on cod was reduced, but not sufficiently to influence future exploitation patterns. One can argue about the effectiveness of RTCs because they do not control effort, but rather displace it, so it is difficult to evaluate their effectiveness in the short term. Moreover, any benefits from RTCs may be partly negated by the increased days-at-sea allocated to participating vessels. On the positive side, the measures were developed with input from stakeholders, and compliance with respect to RTCs via VMS data was encouraging, with vessels moving away from the boundaries of the closed areas. With the emergence of electronic logbook data and closed circuit TV (CCTV) for on-board surveillance, monitoring of catches may improve and create a more-level playing field across sectors of the wider fishing industry. Other recent studies linking catches and effort in mixed demersal fisheries in the EU fisheries include Fcube, the Fleet and Fisheries Forecast (Maravelias *et al.* 2011; Ulrich *et al.* 2011). This useful application attempts to promote fleet and métier management to progress from the traditional single-species approach for routine advisory use. Ulrich *et al.* (2011) concluded that the current single-species management for North Sea cod could not be achieved unless TACs and effort reduction for other species were applied. However, this study differed from Fcube by accounting for changes in fishing power, so can be applied at a finer regional scale.

This study has shown applications for input control for mixed fisheries management and has also complemented other research initiatives, such as recent catch quota trials (FVM 2009) undertaken by the UK, Denmark and Germany using remote electronic monitoring (REM). The inclusion of REM, personal information on skippers (Kirkley *et al.* 1998; Squires & Kirkley 1999), information on gear and technological changes (Marchal *et al.* 2006) and precise time actually fishing should lead to more detailed estimates of effective fishing effort and relationships with fishing mortality at a finer resolution than the ICES rectangle. It will also be important for future studies to take account of other factors, ranging from non-target fish and wider ecosystem impacts to the social and economic implications of effort controls and their impacts on the different submétiers. The movement away from single-species management to the fleet-based management approach applying temporal, spatial and gear-specific control measures under the guidance of the DCF and future CFP could be used to evaluate alternative management strategies in conjunction with stakeholders, so could facilitate implementation and improve fisheries management, including perhaps fairer access to resources.

Acknowledgements

The study was carried out with partial financial support from the European Commission (CAFE project, DG-Fish contract EC FP6 022644) and from Defra, UK (Project MF1201 and M1228), supporting PhD studies at Imperial College, London. I sincerely thank my colleagues Jim Ellis, Georg Engelhard, Chris Lynam and Andy Payne, and Trevor Hutton (CSIRO, Australia), for constructive comments and support, and two anonymous reviewers for valued comments that greatly improved the final manuscript.

References

Abernethy K.E., Trebilcock P., Kebede B., Allison E.H. & Dulvy N.K. (2010) Fuelling the decline in UK fishing communities? *ICES Journal of Marine Science* **67**, 1076–1085.

Agnew D.J., Pearce J., Pramod G., Peatman T., Watson R., Beddington J.R. *et al.* (2009) Estimating the worldwide extent of illegal fishing. *PLoS ONE* **4**, e4570.

Akaike H. (1974) A new look at the statistical model identification. *IEEE Transactions on Automatic Control* **19**, 716–722.

Baum J.K. & Blanchard W. (2010) Inferring shark population trends from generalized linear mixed models of pelagic longline catch and effort data. *Fisheries Research* **102**, 229–239.

Beddington J.R., Agnew D.J. & Clark C.W. (2007) Current problems in the management of marine fisheries. *Science* **316**, 1713–1716.

Bishop J. (2006) Standardizing fishery-dependent catch and effort data in complex fisheries with technology change. *Reviews in Fish Biology and Fisheries* **16**, 21–38.

Bishop J., Venables W.N. & Wang Y.-G. (2004) Analysing commercial catch and effort data from a penaeid trawl fishery. A comparison of linear models, mixed models, and generalized estimating equations approaches. *Fisheries Research* **70**, 179–193.

Bolker B.M., Brooks M.E., Clark C.J., Geange S.W., Poulsen J.R., Stevens M.H.H. *et al.* (2009) Generalized linear mixed models: a practical guide for ecology and evolution. *Trends in Ecology & Evolution* **24**, 127–135.

Branch T.A., Hilborn R., Haynie A.C., Fay G., Flynn L., Griffiths J., *et al.* (2006) Fleet dynamics and fishermen behavior: lessons for fisheries managers. *Canadian Journal of Fisheries and Aquatic Sciences* **63**, 1647–1668.

Butterworth D.S. (1996) A possible alternative approach for generalized linear model analysis of tuna CPUE data. *ICCAT Collective Volume of Scientific Papers* **45**, 123–124.

Copes P. (1986) A critical review of the individual quota as a device in fisheries management. *Land Economics* **62**, 278−291.

Cunningham S. & Gréboval D. (2001) *Managing Fishing Capacity: A Review of Policy and Technical Issues*. FAO Fisheries Technical Paper **409**, 60 pp.

Daan N. (2005) An afterthought: ecosystem metrics and pressure indicators. *ICES Journal of Marine Science* **62**, 612−613.

De Veen J.F. (1976) On the exploitation pattern in the Dutch North Sea sole fishery. ICES Document **CM 1976/F: 19**. 29 pp.

De Veen J.F. (1978) On the selective tidal transport in the migration of North Sea plaice (*Pleuronectes platessa* L.) and other fish species. *Netherlands Journal of Sea Research* **12**, 115−147.

Diggle P.J., Heagerty P., Liang K.-Y. & Zeger S.L. (2002) *Analysis of Longitudinal Data*, 2nd edn. Oxford: Oxford Statistical Science Series **25**, 400 pp.

EC (2000) Data Collection Regulation (EC 1563/2000).

EC (2006a) *Commission Staff Working Paper. Report of the ad hoc Meeting of Independent Experts on Fleet−Fishery Segmentation*, Nantes, France, 12–16 June 2006.

EC (2006b). Regulation 51/2006, fixing for 2006 the fishing opportunities and associated conditions for certain fish stocks and groups of fish stocks, applicable in Community waters and, for Community vessels, in waters where catch limitations are required. Available at: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CONSLEG:2006R0051:20061026:EN:PDF (accessed March 2012).

EC (2006c) Regulation 41/2006, fixing for 2007 the fishing opportunities and associated conditions for certain fish stocks and groups of fish stocks, applicable in Community waters and, for Community vessels, in waters where catch limitations are required. Available at: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2007:015:0001:0213:EN:PDF (accessed March 2012).

EC (2008) Data Collection Framework (EC 199/2008).

Engelhard G.H. (2008) One hundred and twenty years of change in fishing power of English North Sea trawlers. In: A. Payne, J. Cotter & T. Potter (eds) *Advances in Fisheries Science: 50 years on from Beverton and Holt*. Oxford: Blackwell Publishing, pp. 1–25.

FAO (2003) Fisheries management. The ecosystem approach to fisheries. *FAO Technical Guidelines for Responsible Fisheries* **4**, 112.

FVM (2009) *Paving the Way for a New Common Fisheries Policy*. Ministry of Food, Agriculture and Fisheries, Denmark (revised 15 October 2009).

Gauch H.G. (1982) *Multivariate Analysis in Community Ecology. Cambridge Studies in Ecology*. Vol. **1**. Cambridge, UK: Cambridge University Press, 298 pp.

Gréboval D. (1988) Assessing excess fishing capacity at worldwide level. In: D. Gréboval (ed.) *Managing Fishing Capacity: Selected Papers on Underlying Concepts and Issues*. FAO Fisheries Technical Paper **386**, 206 pp.

Helser T.E., Punt A.E. & Methot R.D. (2004) A generalized linear mixed model analysis of a multi-vessel fishery resource survey. *Fisheries Research* **70**, 251–264.

Hilborn R. & Walters C.J. (1992) *Quantitative Fisheries Stock Assessment: Choice, Dynamics and Uncertainty*. New York: Chapman & Hall, 570 pp.

Hinton M.G. & Maunder M.N. (2003) Methods for standardizing CPUE and how to select among them. *ICCAT Collective Volume of Scientific Papers* **56**, 169–177.

Hunter E., Metcalfe J.D. & Reynolds J.D. (2003) Migration route and spawning area fidelity by North Sea plaice. *Proceedings of the Royal Society of London, Series B: Biological Sciences* **270**, 2097–2103.

Hutton T., Mardle S., Pascoe S. & Clark R.A. (2004) Modelling fishing location choice within mixed fisheries: English North Sea beam trawlers in 2000 and 2001. *ICES Journal of Marine Science* **61**, 1443–1452.

ICES (2007) *Report of the Working Group on the Assessment of Demersal Stocks in the North Sea and Skagerrak*. ICES Document **CM 2007/ACFM 18.**

ICES (2009) *Manual for the Offshore Beam Trawl Surveys, Rev. 1.2, June 2009*. Copenhagen: ICES Working Group on Beam Trawl Surveys, 30 pp.

Kirkley J., Squires D. & Strand I. (1998) Characterizing managerial skill and technical efficiency in a fishery. *Journal of Production Analysis* **9**, 145–160.

Mahévas S., Sandon Y. & Biseau A. (2004) Quantification of annual variations in fishing power and explanation of differences in efficiency by technical characteristics: an application to the bottom-trawlers of South Brittany targeting anglerfish from 1983 to 1998. *ICES Journal of Marine Science* **61**, 71–83.

Mahévas S., Vermard Y., Hutton T., Iriondo A., Jadaud A.A., Maravelias C.D. *et al.* (2011) An investigation of human vs. technology-induced variation in catchability for a selection of European fishing fleets. *ICES Journal of Marine Science* **68**, 2252–2263.

Maravelias C.D., Damalas D., Ulrich C., Katsanevakis S. & Hoff A. (2011) Investigating demersal mixed-fisheries management with the Fcube method in the Aegean Sea (eastern Mediterranean). *Fisheries Management and Ecology* **19**, 189–199.

Marchal P. (2008) A comparative analysis of metiers and catch profiles for some French demersal and pelagic fleets. *ICES Journal of Marine Science* **65**, 674–686.

Marchal P., Ulrich C. & Pastoors M. (2002) Area-based management and fishing efficiency. *Aquatic Living Resources* **15**, 73–85.

Marchal P., Ulrich C., Korsbrekke K., Pastoors M. & Rackham B. (2003) Annual trends in catchability and fish stock assessments. *Scientia Marina* **67**, 63–73.

Marchal P., Andersen B., Bromley D., Iriondo A., Mahévas S., Quirijns F., *et al.* (2006) Improving the definition of fishing effort for important European fleets, by accounting for the skipper effect. *Canadian Journal of Fisheries and Aquatic Sciences* **63**, 510–533.

Maunder M.N. & Punt A.E. (2004) Standardizing catch and effort data: a review of recent approaches. *Fisheries Research* **70**, 141–159.

Needle C.L. & Catarino R. (2011) Evaluating the effect of real-time closures on cod targeting. *ICES Journal of Marine Science* **68**, 1647–1655.

Nelder J.A. & Wedderburn R.W.M. (1972) Generalized linear models. *Journal of the Royal Statistical Society, Ser. A* **135**, 370–384.

Ortiz M. & Arocha F. (2004) Alternative error distribution models for the standardization of catch rates of non-target species from a pelagic longline fishery: billfish species in the Venezuelan tuna longline fishery. *Fisheries Research* **70**, 275–297.

Ortiz M., Legault C.M. & Ehrhardt N.M. (2000) An alternative method for estimating bycatch from the US shrimp trawl fishery in the Gulf of Mexico, 1972–1995. *Fishery Bulletin US* **98**, 583–599.

Pauly D., Christensen V., Guénette S., Pitcher T.J., Sumaila U.R., Walters C.J., *et al.* (2002) Towards sustainability in world fisheries. *Nature* **418**, 689–695.

Piet G.J. & Jennings S. (2005) Response of potential community indicators to fishing. *ICES Journal of Marine Science* **62**, 214–225.

Pinheiro J.C. & Bates D.M. (2000) *Mixed-Effects Models in S and S-PLUS*. New York: Springer, 530 pp.

Rijnsdorp A.D. & Pastoors M.A. (1995) Modelling the spatial dynamics and fisheries of North Sea plaice (*Pleuronectes platessa* L.) based on tagging data. *ICES Journal of Marine Science* **52**, 963–980.

Rijnsdorp A.D., Daan N. & Dekker W. (2006) Partial fishing mortality per fishing trip: a useful indicator of effective fishing effort in mixed demersal fisheries. *ICES Journal of Marine Science* **63**, 556–566.

SAS Institute Inc. (1983) *SAS User's Guide*. Cary, NC: SAS Institute Inc.

SAS Institute Inc. (1996) *SAS User's Guide*. Cary, NC: SAS Institute Inc.

SAS Institute Inc. (2006) The GLIMMIX procedure. Available at: http://support.sas.com/rnd/app/papers/glimmix.pdf (accessed June 2012).

Shepherd J.G. (2003) Fishing effort control: could it work under the Common Fisheries Policy? *Fisheries Research* **63**, 149–153.

Squires D. & Kirkley J. (1999) Skipper skill and panel data in fishing industries. *Canadian Journal of Fisheries and Aquatic Sciences* **56**, 2001–2018.

Tascheri R., Saavedra-Nievas J.C. & Roa-Ureta R. (2010) Statistical models to standardize catch rates in the multi-species trawl fishery for Patagonian grenadier (*Macruronus magellanicus*) off southern Chile. *Fisheries Research* **105**, 200–214.

Tidd A.N., Hutton T., Kell L.T. & Padda G. (2011) Exit and entry of fishing vessels: an evaluation of factors affecting investment decisions in the North Sea English beam trawl fleet. *ICES Journal of Marine Science* **68**, 961–971.

Tidd A.N., Hutton T., Kell L.T. & Blanchard J.L. (2012) Dynamic prediction of effort re-allocation in mixed fisheries. *Fisheries Research* **125–126**, 243–253.

UK Fisheries Department. (1988) *Measuring the Catching Capacity of Fishing Vessels*. London: MAFF Consultation Document **CER188F2**.

Ulrich C., Reeves S.A., Vermard Y., Holmes S.J. & Vanhee W. (2011) Reconciling single-species TACs in the North Sea demersal fisheries using the Fcube mixed-fisheries advice framework. *ICES Journal of Marine Science* **68**, 1535–1547.

Venables W.N. & Dichmont C.M. (2004a) GLMs, GAMs and GLMMs: an overview of theory for applications in fisheries research. *Fisheries Research* **70**, 315–333.

Venables W.N. & Dichmont C.M. (2004b) A generalized linear model for catch allocation: an example of Australia's northern prawn fishery. *Fisheries Research* **70**, 405–422.

Vermard Y., Marchal P., Mahévas S. & Thébaud O. (2008) A dynamics model of the Bay of Biscay pelagic fleet simulating fishing trip choice: the response to the closure of the European anchovy (*Engraulis encrasicolus*) fishery in 2005. *Canadian Journal of Fisheries and Aquatic Sciences* **65**, 2444–2453.

Vinther M., Reeves S.A. & Patterson K.R. (2004) From single-species advice to mixed-species management: taking the next step. *ICES Journal of Marine Science* **61**, 1398–1409.

Weninger Q. & McConnell K.E. (2000) Buyback programs in commercial fisheries: efficiency versus transfers. *Canadian Journal of Economics* **33**, 394–412.