Multi-Output Distance Function for the North Sea Beam Trawl Fishery

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Abstract. Interactions between species in a fishery may be either biological (e.g. predator-prey) or technical (e.g. joint production). Technical interactions within fisheries have generally been assumed to exist, although the strength of these interactions has not been previously quantified. In this paper, we estimate a multi-output distance function for the UK North Sea demersal fishery and consider elasticities of substitution between the outputs. The empirical results of the paper have implications for continuing fisheries management in several countries. In particular, they reinforce the need for fisheries managers to consider the technical interactions between species when setting the TACs. Failure to consider these interactions may result in increased discarding in the fishery, and potentially lower than expected future yields.

Key Words: multi-output fishery, distance function, elasticities of substitution, efficiency.

JEL: Q22

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1. Introduction

Fisheries management can impinge on economic efficiency in a number of ways, as it is based on a combination of input (regulating the level of fishing effort) and output controls (regulating the total harvest through total allowable catches (TAC) or individual quotas). This motivated economists, in the last decade, to estimate technical efficiency in fisheries (Salvanes and Steen, 1994; Kirkley et al., 1995, 1998; Campbell and Hand, 1998; Squires and Kirkley, 1999; Grafton et al., 2000; Pascoe et al., 2001, Alvarez and Orea, 2001).[2]

In summary, the literature finds that restrictions on input use may lead to input substitution, resulting in a sub-optimal combination of inputs relative to the unrestricted situation (both in terms of technical and allocative efficiency). Moreover, measures to reduce the ability of fisheries to harvest the resource without reducing the total level of employment may result in contraction or shifts in the production frontier through technological changes. Management may also result in improved input allocative efficiency through removing incentives to overcapitalise. Regarding output controls in fisheries, the literature finds that when changes in quota allocations do not reflect changes in stock conditions, actual catch may diverge from planned catch, and output may be less than efficient given the level of inputs.

An aspect of the fishing activity, which is closely related to efficiency measures, but also affects the effectiveness of fisheries' regulation, is jointness in production. In the case of multi-species fisheries, fishing firms may be exploiting several fish stocks at the same time in a situation where it may be difficult to target specific stocks (by-catch). The challenge is then to correctly model this situation in order to be able to derive reliable policy recommendations with regards to the efficiency implications of the existing regulatory regime.

2. Single vs multi-output production functions in fisheries

A production function defines the relationship between the level of inputs and the resultant level of outputs. It is estimated from observed outputs and input usage and indicates the average level of outputs for a given level of inputs (Schmidt 1986). In fisheries, several studies have estimated production functions at either the individual boat level or total fishery level (e.g. Hannesson 1983, Campbell and Lindner 1990, Squires 1987, Pascoe and Robinson

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[2] See Alvarez (2001) for a survey of the literature.

1998). The objective of these studies was generally to estimate the output elasticities associated with each input, and in some cases the potential for input substitution.

More recently, emphasis has shifted to the estimation of production frontiers. Interest in technical efficiency has largely driven this shift, although there are theoretical reasons why the estimation of production frontiers has advantages over the estimation of production functions (see Kumbhakar 2002). Only limited attempts to estimate stochastic production frontiers for fisheries have been undertaken (Kirkley, Squires and Strand 1995, 1998, Campbell and Hand 1998, Sharma and Leung 1999, Grafton, Squires and Fox 2000, Alvarez 2001, Pascoe, Anderson and de Wilde 2001, Pascoe and Coglan 2002).

A common feature of these studies is the reliance on a single measure of output. This approach has generally been common for the estimation of most production functions in most industries. However, unlike many other industries, fisheries are characterised by joint production. Joint production occurs when firms produce several outputs at the same time. In fisheries, this is due to technological aspects of the production process, in particular technical interdependencies and non-allocable inputs. Resource jointness in fisheries can arise as a result of several reasons. In particular, many species are often found in the same geographical area and will be harvested at the same time as a result of the limited selectivity of the fishing gear.

The use of a singe composite measure of output under such circumstances imposes a number of restrictive assumptions. Summing up the weight of each output assumes that all species are equally important in the catch, which is clearly not the case in fisheries as high volume species often tend to be low value. This can be overcome through incorporating price into the measure, and several of the above studies have used revenue as the output measure. The use of total revenue as the output measure requires the assumption that output prices do not differ between firms, and changes in ‘output’ due to changes in price need to be compensated for. A further method that has been applied in several of the above studies has been to weight the quantity of each output on the basis of its revenue share. This avoids the biases introduced through using prices only, but assumes revenue maximising behaviour and competitive output markets – assumptions that may not be realistic in many instances. Moreover, an aggregate production function imposes the restrictive assumption of separability in inputs and output on the transformation function. This implies that the input mix can be changed significantly without affecting the slope of the production possibility curve and that marginal costs depend only on the output mix, so are independent of the input prices.

An alternative to single output measures is the use of multi-output measures. Several studies have been undertaken assessing technical efficiency and capacity utilisation using Data Envelopment Analysis (DEA) in fisheries (couple of references). A key feature of DEA is that it is directly able to incorporate multiple outputs into the analysis. However, as it is non-parametric it is sensitive to random error, and also does not provide estimates of the impact of individual inputs on the level of outputs, or the relationship between the outputs themselves.

Alvarez and Orea (2001) examined two methods for incorporating multi-outputs in fisheries production functions and compared these with single output measures. The first method – the multi-output production function – involved regressing one (of two) outputs against the other output and set of inputs. The second method – the output oriented distance function – involved a normalised and restricted model that considers the maximal proportional expansion of the output vector given an input vector. Both methods were found to produce similar output elasticities associated with each input, and these were also similar to those derived through the single output production function. Moreover, the specification of the production process as multi-output overcame the problems associated with the implicit assumptions imposed through the different aggregation processes necessary to derive the single composite output measure.

A key criticism of the multi-output production function is that the output selected as the dependent variable plays an asymmetric role, which affects the estimated parameters of the production technology as well as the relevant efficiency score. In contrast, in the output oriented distance function, every output plays the same role, avoiding the asymmetry problem (i.e. the efficiency measures are not output specific but radial). Further, the output oriented distance function has advantages over the other methods in that estimation is possible without separability and jointeness, and information on prices is not required. However, the estimation of the distance function requires the assumption of linear homogeneity in outputs, implicitly implying that not only efficiency but noise are also radial. That is, the influence of noise on one output is the same as that upon another output. This not withstanding, the output-oriented distance function appears to be the most appropriate method for estimating multi-output

3. The Restricted Multi-Output Distance Function

The methodology employed in the study largely follows that used by Fare and Grosskopf (1990), Grosskopf et al. (1995), Coelli and Perelman (1996) and Morrison Paul et al. (2000). These studies largely derive from the initial distance function theory developed by Shephard (1970). Given the existence of a production possibility frontier, the distance that any producer is away from the frontier is a function of the set of inputs used, **x**, and the level of outputs produced, **y**. For the output-oriented model, this can be expressed as

$$D_0(\mathbf{x}, \mathbf{y}) = \min\{\theta : (\mathbf{y}/\theta) \in P(\mathbf{x})\} \qquad \textbf{(1)}$$

where $D_0(\mathbf{x},\mathbf{y})$ is the distance from the firm's output set to the frontier, and θ is the corresponding level of efficiency. The output distance function seeks the largest proportional increase in the observed output vector **y** provided that the expanded vector $(\mathbf{y}/\theta)$ is still an element of the original output set (Grosskopf et al 1995).[3] If the firm is fully efficient, so that it is on the frontier, $D_0(\mathbf{x},\mathbf{y}) = \theta = 1$, where as $D_0(\mathbf{x},\mathbf{y}) = \theta < 1$ indicates that the firm is inefficient. The output distance function is homogeneous of degree 1 in outputs (Shephard 1970).[4]

Fishery models recognise that capital (the vessel) is usually a fixed factor, due to limited second hand markets and high adjustment costs. These models use a restricted profit function, where the fishing vessel is assumed to maximise profits by choosing inputs and harvest level

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[3] Production technology is defined by output sets, $P(\mathbf{x})$, which represents the set of all output vectors, **y**, which can be produced using the input vector, **x**, i.e., $P(\mathbf{x})=\{\mathbf{y} : \mathbf{x} \text{ can produce } \mathbf{y}\}$. The properties of this set are summarised as follows: for each **x**, the output set $P(\mathbf{x})$ is assumed to satisfy (i) $0 \epsilon P(\mathbf{x})$; (ii) non-zero output levels cannot be produced from zero level of inputs; (iii) $P(\mathbf{x})$ satisfies strong disposability of outputs: if $\mathbf{y} \epsilon P(\mathbf{x})$ and $\mathbf{y}^* = \mathbf{y}$ then $y^* \epsilon P(\mathbf{x})$; (iv) $P(\mathbf{x})$ satisfies strong disposability of inputs: if **y** can be produced from **x**, then **y** can be produced from any $\mathbf{x}^* = \mathbf{x}$; (vi) $P(\mathbf{x})$ is bounded (which is essentially a mathematical requirement that implies that we cannot produce unlimited levels of outputs with a given set of inputs); (vii) $P(\mathbf{x})$ is convex (which implies that if two combinations of output levels can be produced with a given input vector **x**, then any average of these output vectors can also be produced; this assumption implicitly requires the commodities to be continuously divisible).

[4] The properties of $D_0(\mathbf{x},\mathbf{y})$ follow directly from the axioms on the technology set and play a major role in efficiency measurement: (i) $D_0(\mathbf{x},\mathbf{y})$ is non-decreasing in **y** and increasing in **x**; (ii) $D_0(\mathbf{x},\mathbf{y})$ is linearly

subject to the size of the vessel used in harvesting. Modelling fishermen behavior with profit functions, however, is appropriate only when the output quantities are choice variables. For the fishing vessel in IVQ regulated fisheries the harvest level is set by the individual quota and is no longer a choice variable, i.e., harvest is an exogenous or restricted factor. Hence the price-taking fishermen maximises profits for a given harvest level H_{it}, or equivalently, minimises the cost of harvesting the given quota, assuming the quota is the only fixed factor, (Asche et al., 2002).

The restricted profit maximization problem can be written as:

$$\begin{aligned}&\Pi^R_{it}(p^P_t, p^S_t, p^C_t, p^A_t, p^O_t, p^K_t, p^E_t) = \\ &\max(p^P_t \cdot y^P_{it} + p^S_t \cdot y^S_{it} + p^C_t \cdot y^C_{it} + p^A_t \cdot y^A_{it} + p^O_t \cdot y^O_{it}) - C_{it}(Y_{it}, p^E_t, p^K_t)\end{aligned} \quad \textbf{(2)}$$

where

$$C_{it}(Y_{it}, p^E_t, p^K_t) = \min p^E_t \cdot x^E_{it} + p^K_t \cdot x^K_{it} : H_{it}(Y_{it}, x^E_{it}, x^K_{it}) = 0 \quad \textbf{(3)}$$

To anticipate empirical estimation, variables are introduced. The vessel and time specific restricted profit function and the cost function are $\Pi^R_{it}(.)$ and $C_{it}(.)$, respectively. Outputs are plaice (y^P_{it}), sole (y^S_{it}), cod (y^C_{it}), angler (y^A_{it}) and other (y^O_{it}); p^P_t, p^S_t p^C_t p^A_t and p^O_t, are respective competitive market prices. Input price vectors for labour (days employed in fishing) x^E_{it} and capital x^K_{it}, are p^E_t and p^K_t, respectively. $\mathbf{Y}_{it}$ is vessel *(i)* and time *(t)*-specific aggregate harvest quantity. By solving for optimal levels of output, one can therefore find the potential rents in such a fishery.[5]

Given the advantages of the distance function discussed in section (2), we model fishing behaviour through a restricted multi-output distance function. The production technology is defined by output sets, $P(\mathbf{X}_{it};\mathbf{H}_{it})$, which represents the set of all output vectors, $\mathbf{Y}_{it}$, which can be produced using the input vector, $\mathbf{X}_{it}$, given that individual fishermen decide the mix of

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homogeneous in **y**; (iii) if **y** belongs to the production possibility set of **x** (i.e., $\mathbf{y} \in P(\mathbf{x})$), then $D_0(\mathbf{x},\mathbf{y}) = 1$; and (iv) distance is equal to unity (i.e., $D_0(\mathbf{x},\mathbf{y})=1$) if **y** belongs to the "frontier" of the production possibility set.

[5] Furthermore, since the TAC is given, if some vessels are to increase their output, others must reduce theirs. As argued by Asche et al. (2002), one can also obtain optimal fleet size, and therefore an indication of the overcapacity in the fishery. This is important information in fisheries managed with IVQs, as it will provide information about the extent to which one has been able to collect the resource rent and how much resource rent is dissipated due to overcapacity in the fishery.

input quantities for a given quota (which can be vessel *(i)* and time *(t)* specific). Quotas restrict the harvest level $\mathbf{H}_{it}$. That is,

$$P(\boldsymbol{X}_{it};\ \boldsymbol{H}_{it}) = \{\boldsymbol{Y}_{it}: \boldsymbol{X}_{it} \text{ can produce } \boldsymbol{Y}_{it} \text{ given } \boldsymbol{H}_{it}\} \qquad \textbf{(4)}$$

For each $\mathbf{X}_{it}$, the output set $P(\mathbf{X}_{it};\ \mathbf{H}_{it})$ is assumed to satisfy the properties mentioned above. The output distance function is defined on the output set, $P(\mathbf{X}_{it};\mathbf{H}_{it})$, as:

$$D^{R}_{oit}(x^{E}_{it}, x^{K}_{it}, y^{P}_{it}, y^{S}_{it}, y^{C}_{it}, y^{A}_{it}, y^{O}_{it}; H_{it}) = \min\{\theta_{it:}: (Y_{it}/\theta_{it}) \in P(X_{it}; H_{it})\} \qquad \textbf{(5)}$$

where $D^{R}_{oit}(.)$, the restricted output distance function, is non-decreasing in outputs and increasing in inputs, linearly homogeneous in outputs, $D^{R}_{oit}(.) = 1$ and $D^{R}_{oit}(.) = 1$ if $\mathbf{Y}_{it}$ belongs to the "frontier" of the production possibility set; θ_{it} measures the proportional (radial) expansion of the output vector that brings the *ith* firm to the efficient frontier.[6]

Shepard (1970) has shown that the output distance function may also be obtained as a profit maximal profit function. This means that equation (5) can alternatively be written as:

$$\begin{aligned} &D^{R}_{oi}(x^{E}_{it}, x^{K}_{it}, y^{P}_{it}, y^{S}_{it}, y^{C}_{it}, y^{A}_{it}, y^{O}_{it}; H_{it}) = \\ &\max_{p^{M}} \{p^{P}_{t} \cdot y^{P}_{it} + p^{S}_{t} \cdot y^{S}_{it} + p^{C}_{t} \cdot y^{C}_{it} + p^{A}_{t} \cdot y^{A}_{it} + p^{O}_{t} \cdot y^{O}_{it} : \Pi^{R}_{it}(.)\} \\ &m = 1, \ldots, 6 \quad \text{outputs} \end{aligned} \qquad \textbf{(6)}$$

4. Econometric Specification

In order to estimate the distance from the frontier, both the frontier itself and the relationship between inputs and outputs need to be determined. This requires some form of multi-output production function $P(\mathbf{x})$ to be specified. The most common functional form applied is the translog production function, as it does not impose restrictive assumptions regarding

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[6] The definition of the output distance function uses *min* (minimum) instead of *inf* (infimum), implying the assumption of the absence of the possibility that the minimum does not exist (i.e., that $\theta = +\infty$ is possible).

substitutability between inputs (and in this case outputs[7]). This is particularly important in this study as a primary objective is to assess the elasticity of substitution between outputs.

The translog distance function with M *(m = 1, 2, ... , M)* outputs and K *(k = 1, 2, ... , K)* inputs, and for I *(i = 1, 2, ... , I)* firms, can be given by:

$$\begin{aligned}\ln D_{0i} = \alpha_0 &+ \sum_m \alpha_m \ln y_{mi} + 0.5\sum_m \sum_n \beta_{mn} \ln y_m \ln y_{ni} \\ &+ \sum_k \alpha_k \ln x_{k,i} + 0.5\sum_k \sum_l \beta_{kl} \ln x_k \ln x_{li} \\ &+ \sum_k \sum_m \beta_{km} \ln x_{ki} \ln y_{mi}\end{aligned} \qquad \textbf{(7)}$$

In order to maintain the homogeneity conditions, a number of restrictions need to be imposed. These conditions require the constraints $\sum_m a_m = 1, \sum_n \beta_{mn} = \sum_m \beta_{km} = 0$, while symmetry restrictions require $\beta_{mn} = \beta_{nm}$ and $\beta_{kl} = \beta_{lk}$. The homogeneity restrictions can be imposed through normalising the function by one of the outputs. This results in:

$$\begin{aligned}\ln D_{0i}/y_{1i} = \alpha_0 &+ \sum_m \alpha_m \ln(y_{mi}/y_{1i}) + 0.5\sum_m \sum_n \beta_{mn} \ln(y_m/y_{1i}) \ln(y_{ni}/y_{1i}) \\ &+ \sum_k \alpha_k \ln x_{k,i} + 0.5\sum_k \sum_l \beta_{kl} \ln x_k \ln x_{li} \\ &+ \sum_k \sum_m \beta_{km} \ln x_{ki} \ln(y_{mi}/y_{1i})\end{aligned} \qquad \textbf{(8)}$$

The level of inefficiency can be estimated from a stochastic frontier production function of the form **y** = f(**x**)+v-u, where *v* is the error term (assumed to be N[0, σ]) and *u* is the one sided inefficiency term that may take one of several distributional forms. The level of efficiency is estimated as the exponent of the negative of the error term (i.e., exp(-u)). Consequently, $\ln D_{0i} = -u_i$, and the normalised equation can be expressed as

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[7] For example, an implication of the Cobb-Douglas production function is that the elasticity of substitution is always 1.

$$
\begin{aligned}
-\ln y_{1i} = \alpha_0 &+ \sum_{m} \alpha_m \ln(y_{mi}/y_{1i}) + 0.5\sum_{m}\sum_{n} \beta_{mn} \ln(y_m/y_{1i}) \ln(y_{ni}/y_{1i}) \\
&+ \sum_{k} \alpha_k \ln x_{k,i} + 0.5\sum_{k}\sum_{l} \beta_{kl} \ln x_k \ln x_{li} \\
&+ \sum_{k}\sum_{m} \beta_{km} \ln x_{ki} \ln(y_{mi}/y_{1i}) + v_i + u_i
\end{aligned}
\qquad \textbf{(9)}
$$

For estimation purposes, the negative sign on the dependent variable can be ignored (i.e., use $ln\ y_1$ rather than $-ln\ y_1$). This results in the signs of the estimated coefficients being reversed, but is more consistent with the expected signs of conventional production functions (Coelli and Perelman 1996), and provides a convenient means of qualitatively assessing the models.

In order to separate the stochastic and inefficiency effects in the model, a distributional assumption has to be made for u_i. Two main distributional assumptions that have been proposed are a normal distribution truncated at zero, $u_j \sim \lfloor N(\mu,\sigma_u^2) \rfloor$ (Aigner, Lovell and Schmidt 1977); and a half-normal distribution truncated at zero, $u_j \sim \lfloor N(0,\sigma_u^2) \rfloor$ (Jondrow *et al.* 1982). In addition, the inefficiency can also be considered to have a time invariant component, such that $u_{i,t} = u_i \exp[\eta(T-t)]$ (Battese and Coelli 1992), where T is the terminal time period (i.e. $u_{i,t} = u_i$ when $t=T$).

4.1 Elasticities of substitution

Following Grosskopf et al (1996), the Allen elasticities of substitution can be directly derived from the distance function, given by

$$
A_{yy'}(x,y) = [D(x,y) + \frac{\partial^2 D(x,y)}{\partial y\, \partial y'}]/[\frac{\partial D(x,y)}{\partial y} * \frac{\partial D(x,y)}{\partial y'}] \qquad \textbf{(10)}
$$

where $A_{yy'}$ is the Allen elasticity of substitution between output y and y'. A negative value indicates the outputs are substitutes, while a positive value indicates complementarity. The size of the value is a measure of the strength of the substitute/complementarity relationship.

In order to estimate the values of the first and second order derivatives, the values of α and β relating to the output over which the production function was normalised need to be derived. This can be done using the homogeneity restrictions that were imposed on the model.

For the purposes of estimating the elasticity of substitution, the signs of the estimated coefficients need to be reversed.

5. The UK North Sea Demersal fishery

The North Sea (ICES Divisions Iva,b,c - see Figure 1) contains a number of interacting multi-species fisheries of great importance to many countries. The North Sea is the major fishing area in European Community waters. Based on the total allowable catches (TACs) and the guide prices for each species, the total value of the allowable catch in 1999 was estimated to be about 1.5 billion Euro (Table 1). This is an underestimate of the true value of landings as the guide prices are generally lower than market prices. However, it provides an indication of the order of magnitude of the value of the fishery. Over half of the combined total allowable catches of all species in all EU waters are taken from the North Sea. Commercial activity in the region is mostly undertaken by fishermen from the countries bordering the North Sea: UK, Denmark, the Netherlands, France, Germany, Belgium and Norway. Transboundary stocks are shared between the EU and Norway.

This study focuses on two main fleet segments that make up the majority of the UK North Sea demersal fleet: the UK beam trawl and the English otter trawl fleet segments.

The UK North Sea beam trawl fleet targets primarily high value flatfish (particularly sole and plaice), but also catches a considerable quantity of cod and anglerfish. In addition, a range of other species is also caught as bycatch in varying, but small, quantities. Most of the stocks exploited by the fleet are heavily over-fished, resulting in a substantial decrease in the level of quota over recent years. In addition, the fishery has been targeted for decommissioning as it is considered to have considerable excess capacity. Fleet size has been almost halved between 1994 and 2000 as a result of the reduced North Sea quotas (pushing some boats into the English Channel and/or Celtic Sea) and decommissioning.

The otter trawlers primarily target cod, haddock, saithe and whiting, but also catch plaice and nethrops. These species comprise 90 per cent of the catch by volume, and a greater proportion by value. In addition, a range of other species is caught as bycatch.

Figure 1. ICES areas

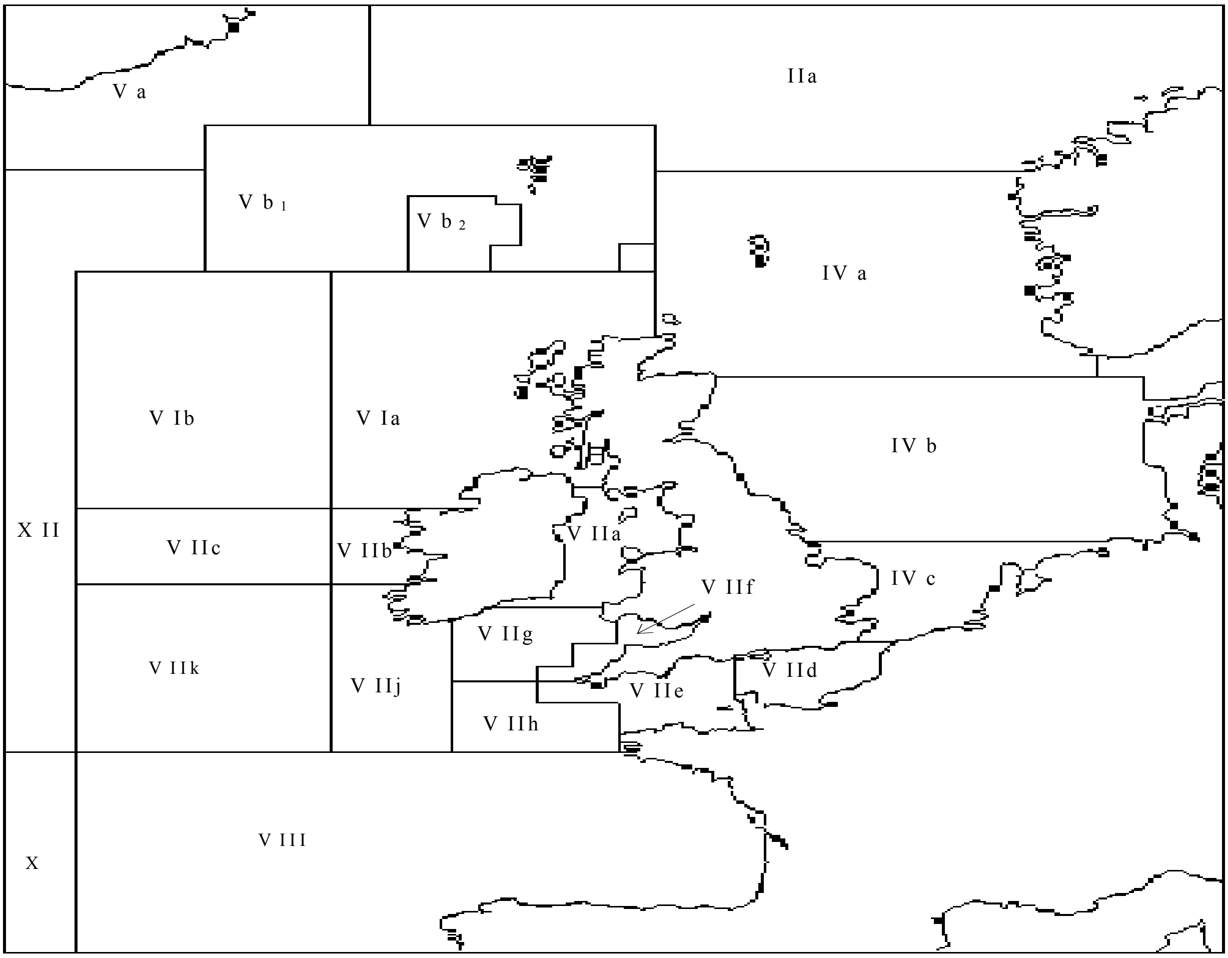

Table 1: TAC allocation for North Sea species[a] (kt) and estimated value[b] (mEuro), 1999

	Belgium	Denmark	France	Germany	Netherlands	Norway	UK	Total	Value
Demersal groundfish[c]									
Cod	4.7	23.9	4.9	12.1	13.1	12.5	52.4	132.4	197.4
Haddock	0.8	5.2	5.8	3.3	0.4	14.9	56.0	88.6	90.9
Whiting	1.2	4.9	8.2	1.4	3.0	4.4	20.9	44.0	38.9
Saithe	0.1	2.3	13.3	6.5	0.0	57.2	4.5	110.0	84.7
Demersal flatfish									
Plaice	6.1	14.9	0.6	6.1	46.6	3.4	23.8	102.0	132.9
Sole	1.6	1.1	0.3	1.2	14.9	0.0	0.9	20.3	131.0
Invertebrates									
Nephrops	0.8	0.8	0.0	0.1	0.4	0.0	12.9	15.2	79.5
Other								1688.4	704.7
Total								2200.9	1460.0

a) Allocation by country based on historical shares of TAC b) Values based on guide prices for 1999 c) includes ICES Division IIa for some species

The key species caught by both groups are subject to quota controls under the European Common Fisheries Policy. Prior to 1998, quota was allocated to the producer organisations (PO) to which the trawlers belonged, based on the rolling track record of the member vessels. This would increase or decrease with the actual catch of the individuals, although the POs were expected to try and keep the total catch within the allocation. Different POs ran different schemes, with some operating an individual transferable quota (ITQ) system (with trade limited to within the PO) and others operating a more competitive TAC system. For the fleet segments examined, most beam trawlers were managed under effectively an ITQ scheme, while most otter trawlers were managed under a pooled quota system. In 1999, the track record system was changed to a fixed quota allocation (FQA). Despite being 'fixed', these could be traded by individuals, either through an annual lease, or through more permanent arrangements (although the process for the latter was generally administrative complex, inhibiting 'permanent' transfers).

Despite being subject to quota controls, these quotas were not binding over the period examined. Since the introduction of the FQAs in 1999, the only binding quotas for North Sea species were for saithe and sole in 2000. For most species, quota uptake ranged between 70 and 90 per cent (DEFRA, 2001). An analysis of the available beam trawl logbook and quota allocation data for 2000 (see next section) found that over 75 per cent of the vessels did not fill their quota allocation, with the remainder exceeding the allocation (assumingly through quota leasing). Given the apparent abundance of quota and the apparent effectiveness of the quota leasing market, it was assumed for the purposes of the study that the quotas were effectively not constraining output.

6. The Dataset

Logbook production data and boat characteristics information from the central fleet registry for the beam and otter trawlers operating in the North Sea were used in the analysis. The data available for the otter trawl fleet relates only to the boats in the fleet registered to English ports. Data on Scottish otter trawlers are held separately, and were not available for this analysis[8]. The logbook data were available on a monthly basis over the 11 year-period 1990-2000.

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[8] This was not a problem for the beam trawl fleet as all UK beam trawlers operate out of English ports.

Over the period, data were available for 58 beam trawlers, although only between 30 and 40 operated in any one year, and 152 otter trawlers, with between 100 and 120 operating in any one year. For both groups, only boats that were still registered in 2000 were included. As noted above, many boats had left the fishery as a result of decommissioning. The boats that left the fishery though the decommissioning scheme were most likely the least efficient, and their inclusion in the earlier years of the analysis (but not the later years) may affect the results. Hence, for consistency, the target population was defined in terms of those boats that were registered in 2000 (even though they may not have participated in the fishery in 2000). A second condition was imposed that the boats must have operated in the fishery in at least three of the 11 years considered in the analysis.

The data set was also subject to further exclusions. For beam trawlers, boats that primarily targeted brown shrimp (*Crangon crangon*) were excluded. For these boats, the catch of the other species considered (see table 2) were negligible, and the fishing operation was considered sufficiently different to exclude from the analysis. Of the remaining vessels, not all boats recorded catch of the key species (plaice) in each year. As this formed the dependent variable in the model, boats that did not record landings of plaice were excluded for that year. Again, boats that did not have catches for at least three years after removing observations without plaice were excluded from the analysis. Similarly for the otter trawlers, boats that did not record landings of cod (the main species) were excluded. As with the beam trawl data, boats that did not have data for at least three years after removing observations without cod were excluded from the analysis. The key characteristics used in the analysis are presented in tables 2 and 3. In most years, data were available for between 30 and 40 beam trawlers, and between 100 and 120 otter trawlers.

Catches of the key species used in the model varied over the period examined, largely as a result of changes in stock conditions. The key species were selected on the basis of both weight and contribution to total value and constituted 90 per cent of the value of total catch. The remaining species were aggregated into and ‘other’ category using a divisia index approach.

Table 2. Average characteristics and catch (kg) of key species, beam trawlers

YEAR	Boats	Engine	Days	Plaice	Sole	Cod	Angler	Other

		power (kW)						
1990	14	954	188	347,343	22,168	10,109	8,778	23,804
1991	27	791	156	194,968	15,038	6,711	6,430	20,054
1992	41	837	158	189,343	8,469	10,651	7,392	25,103
1993	43	815	178	191,841	7,247	14,440	10,688	35,899
1994	39	879	200	195,427	10,165	16,857	13,207	40,579
1995	41	842	196	187,727	9,697	13,557	12,184	38,977
1996	36	899	200	212,235	9,180	15,443	9,085	42,857
1997	38	891	191	238,279	4,163	14,526	11,150	44,008
1998	40	898	188	228,431	6,465	19,562	8,628	44,965
1999	39	898	181	190,520	7,168	13,918	6,175	37,716
2000	35	959	186	295,031	7,784	10,165	7,814	37,474

Table 3. Average characteristics and catch (kg) of key species, otter trawlers

YEAR	Boats	Engine power (kW)	Days	Cod	Haddock	Whiting	Saithe	Nephrops	Plaice	Other
1990	88	223	147	31,171	7,094	8,340	10,539	9,017	3,635	22,358
1991	96	217	140	28,662	6,209	7,959	13,992	7,739	3,701	19,590
1992	99	211	134	29,849	9,198	8,880	5,256	6,348	4,003	18,326
1993	111	217	141	30,841	12,666	9,964	11,149	11,199	2,651	15,493
1994	102	209	117	34,012	10,481	8,898	4,641	1,231	3,423	15,056
1995	110	212	118	36,883	11,484	8,036	10,946	859	4,140	15,572
1996	110	213	119	44,432	13,322	8,679	18,314	1,285	3,377	14,778
1997	124	206	121	38,443	14,757	11264	13,019	1,493	4,411	16,330
1998	123	211	142	62,507	15,709	13,479	10,847	1,623	3,636	15,286
1999	119	216	120	30,794	13,379	11,332	15,770	2,486	3,316	14,693
2000	104	229	122	22,601	10,964	10,377	10,048	3,691	4,352	13,427

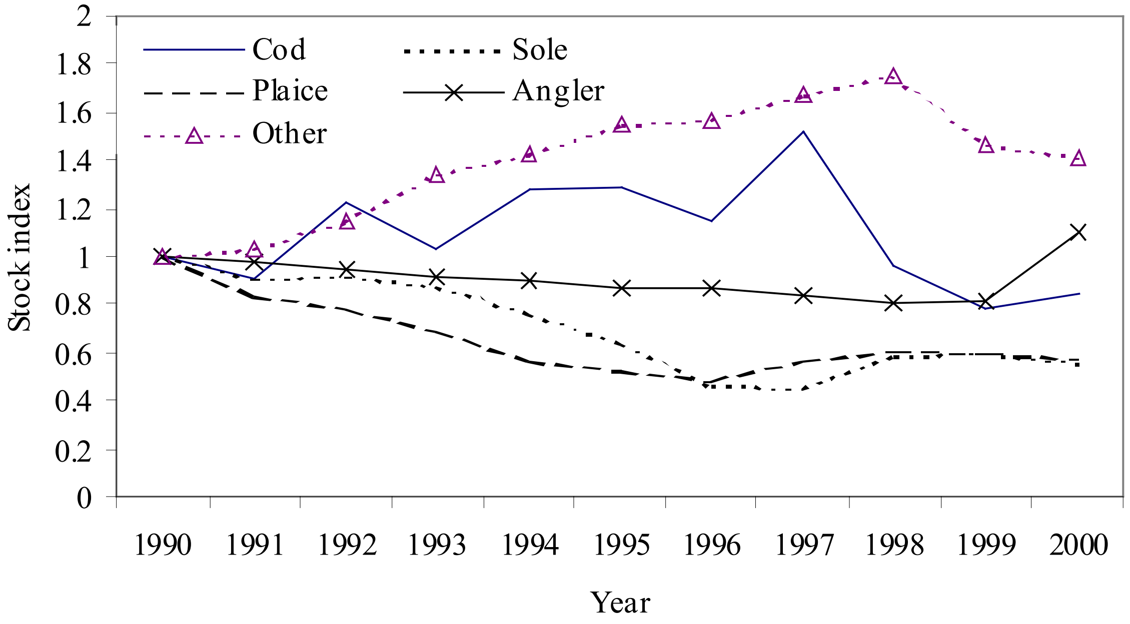
While several physical characteristics were available in the data set (e.g. length, vessel capacity units, width etc), only engine power (kW) was used in the model. Boat deck area (expressed as the product of length and width) was found to be highly correlated with engine power (r=0.94), while vessel capacity units are a composite measure of both boat size and engine power (and, thus, was also highly correlated with engine power). The number of days at sea was also used as a variable in the model, representing the level of capital utilisation.

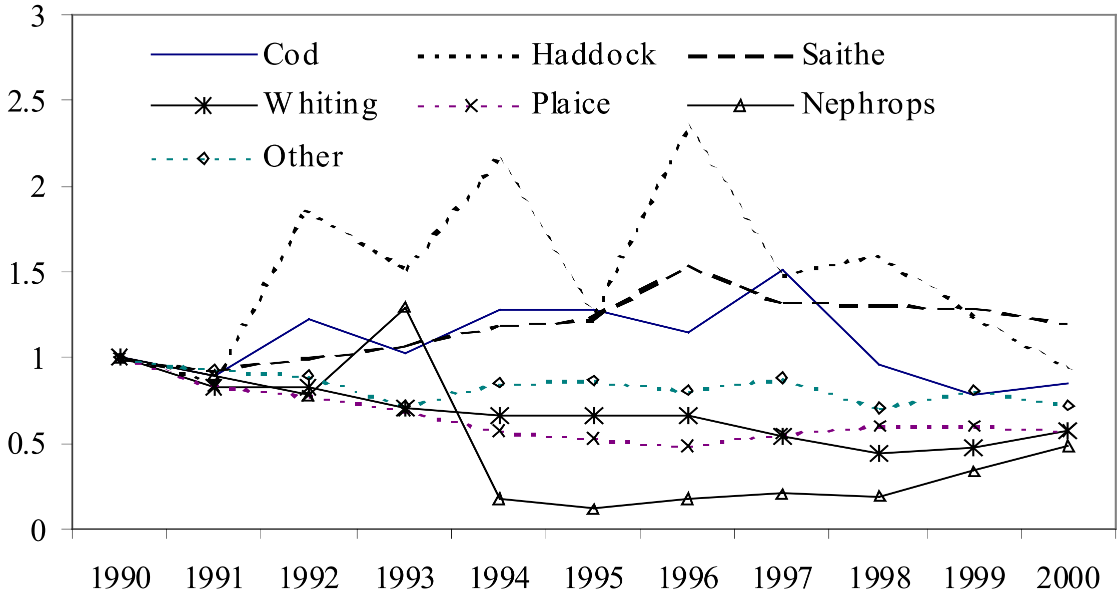
Stock information for the key species examined was available on an annual basis (ICES 2001). Stock indexes were derived based on the total available biomass in each year (with the base year being 1990). Changes in the stock abundance over the period of the data are illustrated in Figure 2. As it can be seen, the different species were subject to differing changes in stock abundance. For the 'other' species, average catch per day fished across the fleet was used to derive the stock index. This approach implicitly assumes that catch per day fished is proportional to the available stock abundance. Individual stock information on many of the species in the 'other' category was not available.

Accounting for variations in stock abundance in fisheries production functions is generally undertaken through either the direct inclusion of the stock index, or through the use of dummy variables. A particular problem exists for the use of stock indexes in multi-output production functions in that each stock measure relates directly to only one of the outputs (although indirectly it may affect the output of the others by affecting fishing patterns). A composite stock variable cannot effectively capture the stock changes of the different species, which do not follow a consistent pattern. Use of dummy variables is also problematic, as a single annual dummy variable cannot adequately represent the different individual stock effects. A series of individual stock dummy variables run into the same problems as the stock indexes, in that they cannot be related to any particular stock. In this study, a further problem was experienced, in that the stock indexes were highly correlated. For example, for the beam trawl fishery, the sole and plaice stock indexes had a correlation coefficient of 0.90, while plaice and 'other' species had a correlation coefficient of 0.80. Initial attempts at incorporating the stock indexes fully into the translog framework resulted in a singular matrix due to the high level of multicollinearity.

To overcome these problems, the catches in each time period were normalised using the stock indexes (i.e. the catch in each time period was divided by the stock index in that time period). This allows the effects of changes in stock size on catch to be incorporated into the analysis, but imposes the implicit assumption of unitary output elasticity with respect to stock size.

Figure 2: Relative stock indexes for a) beam trawl species and b) otter trawl species





7. Empirical Results

The adjusted catches of each species were normalised by plaice and cod for the beam trawl and otter trawl respectively in order to estimate the multi-output production frontier. The data were further normalised by the mean value of each variable, such that the average value of the normalised data was equal to one. This allows the output elasticities with respect to the outputs of the other species and the inputs to be determined directly from the results of the analysis as the α coefficients.

The models were estimated using FRONTER 4.1 (Coelli 1996). A series of tests can be conducted to examine the specification of the models. These are tested through imposing restrictions on the model and using the generalised likelihood ratio statistic (λ) to determine the significance of the restriction. The generalised likelihood ratio statistic is given by $\lambda = -2[\ln\{L(H_0)\} - \ln\{L(H_1)\}]$, where $\ln\{L(H_o)\}$ and $\ln\{L(H_1)\}$ are the values of the log-likelihood function under the null (H_o) and alternative (H_1) hypotheses. The restrictions form the basis of the null hypothesis, with the unrestricted model being the alternative hypothesis. The value of λ has a χ^2 distribution with the number of degrees of freedom given by the number of restrictions imposed.

A key test is the one-sided generalised likelihood ratio-test for the existence of a frontier (i.e., H_o: $\gamma = 0$). As the alternative hypothesis is that $0<\gamma<1$, the test has an asymptotic distribution, the critical values of which are given by Kodde and Palm (1986). If the hypothesis is accepted, then there is no evidence of technical inefficiency in the data and the production frontier is identical to a standard production function.

Several other standard tests are carried out on the specification of the production function and inefficiency distribution. As the basic model is assumed to be have a translog functional form, the hypothesis that the correct functional form of the model is Cobb-Douglas can be imposed by removing the squared and cross product terms from the translog production function (i.e., H_o: $\beta_{i,k} = 0$) and re-estimating the model. Distinguishing between a half normal and a truncated normal distribution as the most appropriate assumption for the inefficiency distribution can be undertaken by running the model under both assumptions. The half-normal distribution is a special case of the truncated normal distribution, and implicitly involves the restriction H_o: $\mu = 0$. Similarly, the hypothesis that efficiency is invariant over time (i.e. H_o: $\eta = 0$) can also be tested. The model is estimated first assuming time variant inefficiency, then restricted by modelling the frontier as time invariant.

The results of the specification tests indicate that the translog is the most appropriate functional form; that inefficiency exists; and that the most appropriate distributional assumption for the inefficiency is a truncated normal distribution with time varying inefficiency (Table 4).

Table 4. Specification tests

	$L(H_0)$	$L(H_1)$	χ^2	Probability
Beam trawl				
$\gamma = 0$	-163.578	-100.621	125.915	<0.01%[a]
$\beta_{i,j} = 0$	-275.485	-100.621	349.728	0.00%
$\mu = 0$	-102.542	-100.621	3.841	5.00%
$\eta = 0$	-108.800	-100.621	16.359	0.01%
Otter trawl				
$\gamma = 0$	-687.097	-481.432	411.331	<0.01%[a]
$\beta_{i,j} = 0$	-810.856	-481.432	658.848	0.00%
$\mu = 0$	-490.692	-481.432	18.521	0.00%
$\eta = 0$	-495.743	-481.432	28.622	0.00%

a) based on the one sided distribution tables developed by Kodde and Palm (1986)

The results for the translog models with the appropriate distributional characteristics are presented in Table 5. Most of the coefficients were found to be significant at the 1 per cent level.

The α coefficients are indicative of the elasticity of the output of the species chosen as the dependent variable with respect to the output of the other species and the inputs. *A priori*, it would be expected that the signs of these coefficients would be negative for the outputs of the other species (assuming some degree of substitution) and positive for the inputs. This was found to be the case for both gear types, with the exception of haddock in the otter trawl model. For both gear types, the output elasticity with respect to days fished was close to unity, while the output elasticity with respect to engine power was less than one. This suggests constant returns with respect to days fished, but diminishing returns with respect to boat size.

The Allen elasticities of substitution were estimated for the various outputs (Table 5, 6 and 7), following the approach proposed by Grosskopf et al (1996). A negative value of the elasticity indicates a substitute, while a positive value indicates a complement. The results suggest that substitution of some species is possible, but this is largely limited to 'bundles' of species. For example, for the beam trawlers, while the main target species is plaice, it appears possible to target sole to some degree. However, increasing sole output also increases the catch of anglerfish and ‘other’ species. Similarly, the fisher could increase the catch of cod, but also ‘other’ species. For the otter trawlers, there appears to be two available strategies, with cod, whiting and plaice being one group, and haddock, saithe, nephrops and ‘other’ being an alternative bundle.

In most cases, the potential of substitutability between the main species and the alternative species is relatively small. For example, while cod and haddock (the two main species) are substitutes for the otter trawlers, the elasticity of substitution is small, so the practical potential for substitution is limited. Similarly, the elasticity of substitution between sole and plaice (the two main species) for the beam trawlers is small, indicating only limited substitution potential.

Table 5. MLE results for the two fleet segments

	Beam trawl				Otter trawl		
	Coeff	SE	t-stat		Coeff	SE	t-stat
Constant	0.731	0.081	9.054***	Constant	1.024	0.082	12.411***
Cod*	-0.036	0.024	-1.531	Haddock*	0.121	0.012	9.752***
Sole*	-0.233	0.016	-14.331***	Whiting*	-0.092	0.012	-7.338***
Angler*	-0.057	0.013	-4.265***	Saithe*	-0.064	0.008	-8.016***
Other*	-0.246	0.036	-6.750***	Nephrops*	-0.054	0.006	-9.064***
KW	0.654	0.069	9.470***	plaice*	-0.129	0.015	-8.561***
Days	1.018	0.053	19.061***	other*	-0.493	0.019	-26.379***
Cod*^{2}	-0.009	0.009	-0.988	KW	0.835	0.068	12.358***
Sole*^{2}	-0.012	0.003	-3.758***	Days	0.978	0.029	33.691***
Angler*^{2}	-0.012	0.003	-4.560***	Haddock*^{2}	0.009	0.003	3.529***
Other*^{2}	-0.034	0.008	-4.433***	Whiting*^{2}	-0.006	0.002	-3.582***
KW^2	-0.036	0.094	-0.383	Saithe*^{2}	0.002	0.001	1.604
Days^2	0.032	0.048	0.676	Nephrops*^{2}	-0.001	0.001	-1.047
Cod*sole*	0.008	0.012	0.639	Plaice*^{2}	-0.010	0.003	-4.000***
Cod*angler*	0.008	0.009	0.823	Other*^{2}	-0.016	0.005	-3.220***
Cod*other*	-0.013	0.016	-0.809***	KW^2	0.008	0.105	0.077
Sole*angler*	-0.006	0.006	-1.057***	Days^2	-0.011	0.026	-0.415
Sole*other*	-0.041	0.013	-3.220	Had*wht*	-0.015	0.004	-4.107***
Angler*other*	0.027	0.010	2.783	Had*saithe*	0.015	0.004	4.086***
Kw days	-0.041	0.058	-0.704	Had*nep*	0.003	0.002	1.821*
Kw cod*	0.000	0.036	0.008	Had*plaice*	-0.015	0.005	-3.086***
Kw sole*	0.168	0.024	6.904***	Had*other*	0.023	0.006	3.468***
Kw ang*	0.018	0.014	1.270	whit*saithe*	0.000	0.003	0.065
Kw other*	-0.241	0.045	-5.389***	Whi*neph*	0.003	0.002	1.219
Days cod*	0.040	0.036	1.108	Whi*plaice*	0.002	0.003	0.868
Days sole*	-0.057	0.021	-2.682***	Whi*other*	0.017	0.004	3.945***
Days ang*	-0.043	0.016	-2.679***	Saithe*nep*	0.000	0.001	0.446
Days other*	0.075	0.037	2.047**	saithe*plaice*	0.007	0.004	1.756*
σ^2	2.650	0.830	3.192***	Saithe*other*	-0.039	0.005	-7.811***
γ	0.974	0.008	115.683***	Nep*plaice*	0.007	0.003	2.111**
μ	-3.214	0.616	-5.221***	Nep*other*	-0.021	0.004	-4.845***
η	-0.065	0.014	-4.726***	plaice*other*	0.023	0.005	4.133***
				Kw days	-0.045	0.067	-0.671
				Kw had*	-0.095	0.024	-4.029***
				Kw whi*	0.050	0.020	2.542**
				Kw saithe*	0.005	0.013	0.340
				Kw neph*	0.037	0.013	2.775***
				Kw plaice*	0.023	0.026	0.862
				Kw other*	0.077	0.028	2.753***
				Days had*	0.046	0.011	4.321***
				Days whi*	-0.015	0.013	-1.154
				Days saithe*	0.022	0.008	2.789***
				Days neph*	-0.021	0.006	-3.251***
				Days plaice*	-0.020	0.017	-1.174
				Days other*	-0.037	0.018	-2.050**
				σ^2	0.240	0.025	9.539***
				γ	0.617	0.030	20.634***
				μ	0.770	0.067	11.427***
				η	0.023	0.004	5.604***

*** significant at the 1% level; ** significant at the 5% level; * significant at the 10% level.

Table 6. Elasticity of substitution: beam trawl

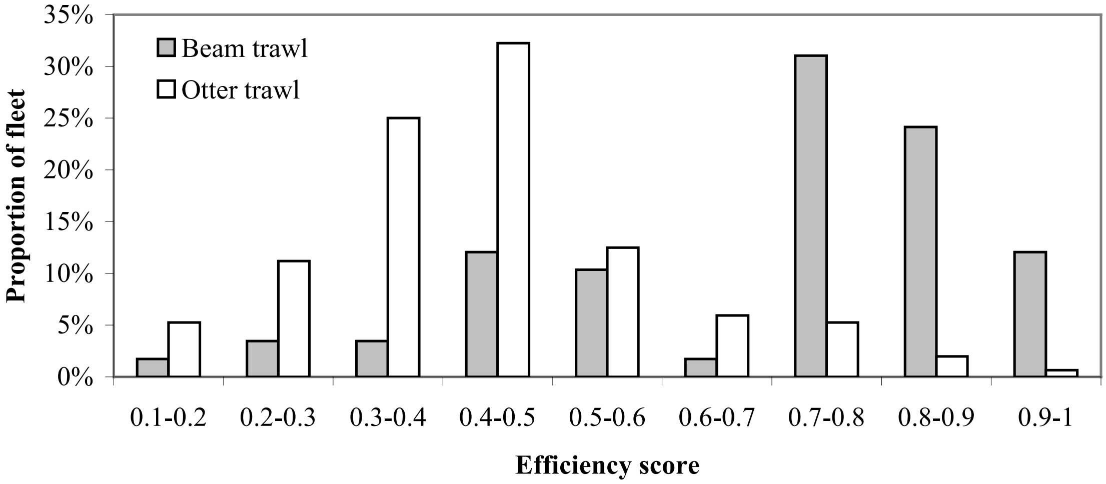
	Plaice	Sole	Cod	Angler	Other
Plaice	-				
Sole	-0.373	-			
Cod	-0.291	-0.659	-		
Angler	0.465	0.346	-2.653	-	
Other	-1.808	0.513	1.026	-1.391	-

Table 7. Elasticity of substitution: otter trawl

	Cod	Haddock	Whiting	Saithe	Nephrops	Plaice	Other
Cod	-						
Haddock	-0.247	-					
Whiting	0.029	-0.570	-				
Saithe	-0.347	0.820	-0.016	-			
Nephrops	-0.247	0.214	-0.237	-0.053	-		
Plaice	0.281	-0.411	-0.083	-0.370	-0.448	-	
Other	-0.043	0.164	-0.163	0.542	0.345	-0.154	-

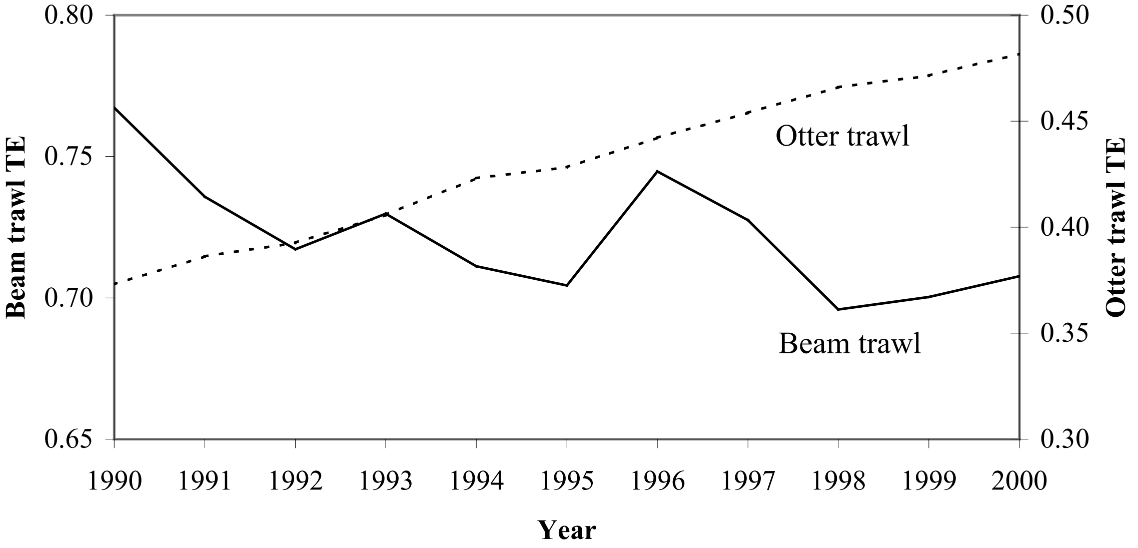
The estimated distributions of efficiency for the two fleet segments differed substantially (Figure 3). Over two thirds of the beam trawlers were more than 70 per cent efficient on average over the period of the data. In contrast, over 90 per cent of the otter trawlers were less than 70 per cent efficient on average.

Figure 3. Distribution of average individual vessel efficiency over the period 1990-2000.



From the model results (Table 5), average individual otter trawl efficiency increased by around 2.3 per cent a year. The removal and replacement of less efficient otter trawlers over the time period resulted in a slight additional increase in average efficiency for the fleet segment as a whole, with an average rate of efficiency increase of around 2.6 per cent (Figure 4). In contrast, average individual efficiency of the beam trawlers decreased by 6.5 per cent a year (Table 5), while removal of the lesser efficient vessels (and introduction of more efficient vessels into the panel) resulted in an overall average decline in the efficiency of the fleet segment of around 1 per cent.

Figure 4. Average vessel efficiency over the period 1990-2000.



A decline in average individual vessel efficiency of Dutch beam trawlers operating in the North Sea was also observed over the same period (Pascoe et al 2001). This was attributed to increased crowding pressure, as TACs for sole and plaice were reduced while fleet sizes remained relatively constant. For the UK fleet, total beam trawl numbers effectively halved over the period examined, reducing the potential increase in crowding externalities. However, as overall international pressure on these shared stocks did not decrease at the same rate, this would still have negatively impinged on the efficiency of the UK vessels.

8. Concluding Remarks

Interactions between species in a fishery may be either biological (e.g. predator-prey) or technical (i.e. joint production). Technical interactions within fisheries have generally been assumed to exist, although the strength of the interaction has not been previously quantified. Most previous studies of production functions and frontiers in fisheries have generally applied a composite output measure on the assumption that applying a set of inputs to a given set of fish stocks (again, usually expressed as a composite stock measure) results in a given level of total output. Alvarez and Orea (2001) examined both multi-output production functions and multi-output distance functions for two species (one being a composite bycatch ‘species’), but did not extend their analysis to consider elasticities of substitution between the outputs.

A key difficulty with the methodology employed in this study was the treatment of the fish stock. While stock measures for each of the species were available, incorporating these into the production function was not feasible. The high correlation between stock size and output of a species (as would be expected) results in substantial multicollinearity in the analysis. Normalising the output data using the associated stock index allowed the changes in output due to stock changes to be taken into account, but necessitated the assumption of a unitary elasticity with respect to stock size. This assumption is most likely valid given the nature of the resource, in that it is widely dispersed, fairly uniform in density across its range and exploited across its whole range. Elasticities greater than one are associated with stocks that are characterised by small areas of high density and large areas of low density, such that catch rates fall rapidly as the aggregations are depleted and the lower density areas are exploited. In contrast, elasticities less than one are associated with stocks that are highly aggregated over a relatively small area (e.g. spawning aggregations), or are exploited in a sequential pattern (i.e. move onto the next area as the catch rates start to decline). In both cases, catch rates decline only marginally as the stock is depleted (until, of course, the whole stock is depleted) (Hilborn and Walters 1992).

Excluding the stock from the production frontier does not allow the effects of changes in stock size on targeting behaviour to be examined. A high relative stock abundance of a species would result in its cost per unit capture decreasing (relative to the other species with lower stock abundances), and may encourage some change in targeting behaviour (i.e. output substitution) if possible. However, high stock abundance resulting in high catches may also result in lower prices, so the incentives to change targeting behaviour may be less than expected. In either case, these effects cannot be captured (and are effectively assumed to be zero) through the exclusion of stock. However, as the elasticity of substitution is a technical (rather than economic) measure, if these factors had influenced targeting behaviour and had resulted in changes in output composition then they should have been identified through the interaction terms in the model. The fact that some substitution has been observed in the data may be a direct result of these factors.

The results of the study have implications for the continuing management of the fishery. In many countries, including the European Union, pressure is often placed on policy makers to allow fishers to catch as much as possible given the natural constraints of the resource. As a result, total allowable catches (TACs) are generally set on the basis of the status of the stock of the individual species rather than on the basis of the technical interactions between the species. This is particularly the case when stocks of some species are severely depressed, requiring substantial decreases in the allowable catch. In such cases, pressure is often placed on policy makers to increase the TACs of less biologically vulnerable species in order to reduce the impact of the reduced catch of the vulnerable species on fisher income. In the case of the North Sea stocks, the technical interaction between haddock, cod and whiting, for example, has been recognised by fisheries scientists, and advice to policy makers has been to control the catches of these species in relation to each other (ICES 2001).

The decline in the North Sea cod stock has resulted in substantial declines in allowable catches in a bid to avoid stock collapse and allow the stock to recover. In 2000, the North Sea cod stock was estimated to be roughly 20 per cent of the level of population of mature fish required for sound recruitment (the Bpa, or "Biomass according to the precautionary approach"). A "recovery programme" was instigated with the aim of enabling the stock of mature fish to increase by 30 per cent a year until the Bpa level has been achieved. The Total Allowable Catch for cod in the North Sea was reduced from 81,000 tonnes in 2000 to 48,600 tonnes in 2001, and further reduced to 41,600 tonnes in 2002 (European Commission 2000, 2001, 2002).

In contrast, North Sea TACs of both haddock and saithe were increased by 62 and 55 per cent respectively between 2001 and 2002. The increase in stock that is presumed to underly these TAC increases will result in an increased proportion of these species in the catch, ceteris paribus. However, stocks of these species are still considered low (ICES 2001), and it is likely that the TACs increases are, in part, a means of 'softening' the impact of the decreased cod TACs. Given the limited substitutability between cod and haddock (and also saithe, which is complementary to haddock), the disparity in the TACs may lead to increased discarding of over-quota cod, provided it is economically viable to continue to fish for haddock and saithe without the additional revenue derived from cod[9].

For the beam trawl fleet, scientific advice for 2002 for the two main species was a 30 per cent reduction in the TAC of plaice and 20 per cent reduction in the TAC of sole in the North Sea (ICES 2001). Recognition was again given to the joint nature of the output of the two species in the scientific advice. Final changes in TACs were, in contrast, less than 5 per cent decrease for plaice and 16 per cent for sole, (European Commission 2002 (and previous years)). Again, given the limited substitutability between sole and plaice, the incompatible TACs may result in increased discarding of sole. However, as sole is substantially more valuable on a per unit basis, it may not be economically viable for fishers to land only plaice and discard sole, resulting in either the TAC for plaice not being filled, or providing incentives to land over-quota catch of sole illegally.

The results of the study reinforce the need for fisheries managers to consider the technical interactions between species when setting the TACs. These interactions have been long recognised by fisheries scientists, and have been generally assumed to exist by fisheries economists. Failure to consider these interactions may result in increased discarding in the fishery, and potentially lower than expected future yields.

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[9] The economic incentives to discard fish has been well established in the literature. See for example Anderson (1994), Arnason (1994) and Pascoe (1998).

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