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Quantification of annual variations in fishing power due to vessel characteristics: an application to the bottom-trawlers of South-Brittany targeting anglerfish (*Lophius budegassa* and *Lophius piscatorius*)

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We present a method based on generalised linear models fitted to CPUE data to quantify the changes in fishing power in a fleet targeting a particular species. Changes in the fleet's fishing power are differentiated from variations in population abundance through the use of an abundance index estimated from the CPUE of an index vessel catching the species as by-catch. Observed inter-vessel differences in efficiency are then explained by vessel characteristics such as gear used, engine power, length of headline and ground rope, availability of GPS and skipper skills. The application of the method to the French bottom-trawlers targeting anglerfish in the Bay of Biscay and in the Celtic Sea during the period 1983–1998 reveals that fishing gear (twin or simple trawls) and engine power are the most important variables for explaining differences in fishing power.

Nous présentons une méthode basée sur l'utilisation de modèles linéaires généralisés ajustés à des données de CPUE pour quantifier les changements de puissances de pêche dans une flottille ciblant une espèce particulière. Les changements de puissance de pêche sont distingués des variations d'abondance de la population en utilisant un indice d'abondance estimé à partir des CPUE d'un bateau témoin capturant cette espèce de manière accessoire. Les différences d'efficacité observées entre les bateaux sont ensuite expliquées par les caractéristiques techniques telles que l'engin utilisé, la puissance motrice, la longueur de la corde de dos, le bourrelet, la possession d'un GPS et l'expérience du capitaine. L'application de la méthode aux chalutiers de fond français ciblant la baudroie dans le golfe de Gascogne et la mer Celtique sur la période 1983–1998 a montré que la puissance motrice et l'engin de pêche (chalut jumeau ou simple) étaient les facteurs qui expliquaient le plus les différences de puissance de pêche.

Keywords: abundance index, Bay of Biscay, catches per unit of effort (CPUE), Celtic Sea, generalised linear models, métier, twin trawls.

Mot-clés: Baudroies, Captures par unité d'effort (CPUE), chaluts jumeaux, golfe de Gascogne, indice d'abondance, mer Celtique, métier, Modèles Linéaires Généralisés, Puissance de pêche.

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Introduction

Catches and fishing effort are basic inputs for assessment and management of marine resources (Beverton and Holt, 1954; Gulland, 1956). The use of catch per unit of effort (CPUE) computed with non-standardised effort data for tuning Virtual Population Analysis (VPA) may lead to errors in stock assessments. Management attempts to reduce fishing effort may not have the desired effects if individual vessel efficiency is not taken into account. In mixed fisheries (multi-fleet, multi-species) it is essential to distinguish nominal fishing effort (Gulland, 1956),

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commonly measured as fishing time for trawlers, from effective fishing effort (Stocker and Fournier, 1981; Biseau, 1998), which is more closely linked to fishing mortality. The same nominal effort will not have the same impact if it is applied by a vessel targeting a given species in contrast to a vessel catching that species as by-catch. Similarly, identical nominal efforts exerted in two different years, say 1983 and 1998, might not have the same impact due to improvements in gear, changes of vessel characteristics, new equipment and improvement of skipper skills with time (Gulland, 1983). Effective effort is an indicator of fishing pressure whereas nominal effort is a management quantity. Hence, to obtain reliable diagnostics for the state of fish stocks, and to ensure that management measures meet conservation requirements, it is important to understand the relationship between fishing effort and fishing mortality by quantifying fishing efficiency and its evolution (Sampson, 1993). Relative fishing efficiency, also called fishing power, is defined as the ratio between effective and nominal effort.

Numerous approaches have been developed to quantify relative fishing efficiency. Beverton and Holt (1954) based their method on the relationship between the catch rate of a given vessel (or the whole fleet) and the catch rate of a standard vessel. Linear models have been used to estimate fishing power while taking into account spatial–temporal heterogeneity of fish-populations and fishing activity. Gulland (1956) and Robson (1966) introduced the multiplicative model to describe fishing power. It is based on the assumption that for any given vessel, the catches of a species are the product of catchability (dependent on the fishing efficiency and on the accessibility–vulnerability of the species), nominal effort and population abundance. Variations in log-transformed CPUE data are traditionally described using linear models with temporal and spatial explanatory variables in single species fishery or in mixed fishery (Laurec and Gall, 1975; Gavaris, 1980). When residuals of such model give indication of more complex heterogeneity than could be explained by a simple spatial and temporal change in CPUE data, it is common either to include interactions between these effects (Francis, 1974; Large, 1992), or to consider the importance of environmental (Allen and Punsly, 1984; Gaertner *et al.*, 1999) or economic variables (Kirkley *et al.*, 1995; Squires and Kirkley, 1999). Fishing power has also been studied with indirect methods using fishing mortalities estimated by cohort analysis (Gascuel *et al.*, 1993; Paloheimo and Cheng, 1993; Pascoe and Robinson, 1996; Millisher *et al.*, 1999). The drawback of these methods is the underlying and commonly unverified assumption of constant catchability used for the estimation of fishing mortality. Given the estimation of fishing efficiency for each vessel of a fleet, identifying the most influential elements that affect a vessel's performance is an important step towards successful fisheries management.

Variability in fishing power has been described by many authors. For instance, Large (1992) found interactions between the year and vessel effects when studying the Western English Channel sole fishery and suggested using the estimated interactions to study trends in fishing power. By analysing the variations in fishing mortalities estimated from an age-structured assessment model, Pascoe and Robinson (1996) quantified changes in fishing efficiency by comparison with a reference year. Marchal *et al.* (2001) have analysed the temporal dynamics in fishing power for a Danish cod fishery by defining an index of fishing power (IFP). This index is a ratio of the CPUE of the vessels of the studied fleet and a subset of vessels from the fleet characterised by small variations in fishing power. Assuming that catchability can be decomposed into a component independent of abundance (the fishing power) and a component dependent on population abundance, the IFP should be devoid of temporal variations in abundance. Variations in the IFP allowed the authors to quantify trends in the fishing power of the fleet. However, the spatial heterogeneity of population abundance was not taken into account in this model. Many authors have already shown the importance of technical factors in fishing power differences such as instrumentation (Robins *et al.*, 1998), vessel tonnage (Goni *et al.*, 1999), bird radar (Gaertner *et al.*, 1999), vessel length and engine power (Biseau *et al.*, 1999b, Salthaug and Godo, 2001).

In this paper, we propose a method to quantify the temporal change in fishing power with respect to a particular species for a given fleet. Our method consists of the following steps: (1) an index of abundance variation is calculated using the CPUE data of a particular index vessel; (2) the index is then used to remove the variability associated with the abundance from the fleet CPUE data. A generalised linear model is applied in order to estimate the change in fishing power over the study period; (3) vessel equipment or crew explain differences in an individual vessel's fishing powers. Following the models developed by Robson (1966) and Gavaris (1980), this approach is based on an explicit distinction between CPUE variations due to stock abundance fluctuations and those due to changes in efficiency. Spatial and seasonal heterogeneity are also taken into account. To distinguish between the two causes of CPUE variations, we use an index vessel in which the species of interest is a by-catch. The CPUE of the index vessel is assumed to be proportional to population abundance as fishing effort is applied randomly with respect to the species of interest. The method is applied to the French bottom-trawlers targeting anglerfish (*Lophius budegassa* and *Lophius piscatorius*) in the Bay of Biscay and in the Celtic Sea.

Methods

CPUE model

CPUE series (catch C divided by nominal effort E) are not considered to be good indices of population abundances

(Gavaris, 1980; Gillis and Peterman, 1998; Harley *et al.*, 2001). Improvements in fishing efficiency with time, differences in efficiency between vessels in a fleet and spatial heterogeneity of the resource accessibility result in CPUE data that are non-proportional to population abundance. Therefore, it is necessary to make CPUE series consistent by modelling the catchability coefficient describing these variations. A realistic model for CPUE is:

$$C/E = a\,P\,N \tag{1}$$

where a denotes the coefficient of accessibility–vulnerability of the target population and P describes the fishing power of the vessel or the fleet catching the population of abundance N. This model allows analysis of CPUE data per vessel and per fishing sequence in order to estimate the relative fishing power of each vessel within a fleet and the change in efficiency over time.

Fishing power analysis traditionally uses linear models on log-transformed CPUE data. In this study, generalised linear model (McCullagh and Nelder, 1989) have been used assuming a Gamma error distribution. The Gamma distribution provides a useful representation of many biological data, mimicking closely a normal or lognormal distribution while representing a positive random variable (Johnson *et al.*, 1994). This distribution is expected to be most appropriate to describe CPUE data of a target species (Smith and Showell, 1996; Stefansson, 1996; Goni *et al.*, 1999).

The GLM approach is particularly suited as it allows analysis of CPUE data following a non-normal distribution and also avoids bias due to back-transformation (Laurent, 1963). The process in model fitting requires first the selection of the most appropriate covariates based on an exploratory analysis. The adequacy of a GLM model to the data and the goodness-of-fit were evaluated using residuals, comparing the likelihood using log-likelihood ratio statistics (also called deviance) or using Akaike's Information Criteria (AIC) (Akaike, 1974). The deviance residuals against the fitted values are expected to present no systematic pattern and to be normality distributed (McCullagh and Nelder, 1989). The analysis of deviance (measure of discrepancy) relies on the χ^2 approximation for differences between deviances for nested models. To select a parsimonious model, the most widespread method based on the minimization of the AIC is the stepwise regression. The main drawback of this modelling approach is the confounding of temporal variations in Fp (Equation (1)), due to population abundance variations and efficiency gains of the fleet. To overcome this difficulty, we constructed an annual index of population abundance using the CPUE of an index vessel.

Abundance index model

The following generalised linear model is fitted to the CPUE data of the index vessel whose efficiency is known to have remained constant over the study period although the actual value is unknown:

$$E[\mathrm{CPUE}] = \exp(\beta_{\mathrm{year}} + \beta_{\mathrm{month}} + \beta_{\mathrm{area}}) \tag{2}$$

where E[CPUE] denotes the expected CPUE value. The error of the model is assumed to follow a Gamma distribution and using a log-link function, which relates the linear predictor $(\beta_{\mathrm{year}} + \beta_{\mathrm{month}} + \beta_{\mathrm{area}})$ to the expected CPUE value. Generalised linear model with a Gamma distribution allow a variety of link functions (e.g. identity, logarithm and inverse) but to consider multiplicative effects on the response scale to be consistent with Equation (1), the logarithmic function is more relevant. As if to estimate parameters in a classical multiple regression, constraints on the parameters (also called contrasts) need to be defined: the first modality of each variable is the reference modality (equal to 0), making parameter estimates directly interpretable (Venables and Ripley, 1999). Given the assumption that the CPUE of the index vessel is proportional to the abundance of the species of interest, the maximum likelihood estimates of the year effects are the values for each year of the relative index of abundance. Since these estimators are normally distributed, confidence intervals of each estimate can be easily constructed (Dobson, 1990).

Let $y = 1$ be the first year of the study, N(y) the abundance in year y and β_y the multiplicative coefficient which allows calculation of the abundance in year y from $N(1): N(y) = \beta_y N(1)$. This coefficient is a relative index of abundance taking the first year as the reference year. If we assume that variations in abundance are annual and using Equation (1), for each fishing sequence in year y, the scaled CPUE is of the form:

$$\frac{C(\text{fishing sequence})}{\beta(y)E(\text{fishing sequence})} = aPN.$$

We then note $\mathrm{CPUE_C}$, the CPUE of the fleet corrected for annual variations in abundance:

$$\mathrm{CPUE_C} = \mathrm{CPUE}(\text{fishing sequence})/\beta_{\mathrm{year}}.$$

Fishing power model

To model the evolution in fishing power of each vessel in the fleet over the study period, the following full model is formulated:

$$E[\mathrm{CPUE}] = \exp(\beta_{\mathrm{vessel}} + \beta_{\mathrm{year}} + \beta_{\mathrm{month}} + \beta_{\mathrm{métier}} + \beta_{\mathrm{area}}). \tag{3}$$

Like abundance index model (Equation (2)), the error is assumed to follow a Gamma distribution with a log-link function. In a model with only main effects, the year effect takes into account the annual variations in fishing power of the fleet while the month effect characterises seasonal variations in harvesting practices (Laurec and Gall, 1975). The vessel effect quantifies the vessel fishing power during the whole period. The métier variable describes the fishing strategy of the vessel during a fishing sequence characterised by different targeting levels of the species of interest (Stocker and Fournier, 1981; Biseau, 1998; Pelletier and Ferraris, 2000; Marchal *et al.*, 2001). The strategy may change with the season and implies a particular choice of fishing area. Thus, if the métier variable is well defined, we can assume that the month and area effects are free of variations in efficiency and no interaction between month and area should be found. Area effects then describe spatial variations in abundance and catchability and the métier effect quantifies the impact of efficiency due to fishing strategy. This model without any interaction between covariates should be the result of the exploratory data analysis and of a selection model process based on the Chi-square test and on the AIC.

Differences in efficiency and technical characteristics

To evaluate and understand the differences in vessel and gear-related efficiency within the fleet, the estimated relative fishing power of each vessel (relative to the reference vessel because of contrasts) was extracted from the fitted model (Equation (3)). A linear model (Equation (4)) was then fitted to the values of relative individual fishing power using vessel specific explanatory variables. These included: date of gear change, average engine power over study period, date of GPS installation, change in number of years with last skipper, headline length, ground rope type

$$\text{vessel coef} \sim \text{variable} + \varepsilon. \qquad (4)$$

Each explanatory variable was tested individually to avoid problems associated with co-linearity.

Materials

Anglerfish catches (comprising two species – *L. piscatorius* and *L. Budegassa*) are an important component of mixed fisheries taking hake, megrim, cod and Nephrops. A trawl fishery by Spanish and French vessels developed in the Celtic Sea (ICES Divisions VIIb–k) and Bay of Biscay (ICES Divisions VIIIa, b, d) (Figure 1) in the 1970s, and overall annual landings may have attained 35 000–40 000 t. TACs have been set for these species but for most years these are much higher than the actual landings. The spawning stock biomass (SSB) of both species has been fluctuating over the past 15 years and is presently decreasing. Spawning stock biomass of *L. piscatorius* is currently just below the biomass precautionary approach reference points (below which there is a high risk of a serious decline in recruitment), while just above for *L. budegassa* (ICES, 2002). Bottom-trawlers operating from Southern Brittany and harvesting anglerfish from 1983 to 1998 were studied. This fishery is particularly interesting for analysing fishing power since a new type of gear (twin bottom-trawls, with the same selectivity properties as single trawls) appeared at the end of the 1980s and might be responsible for the observed increases in catches. Unfortunately, the new trawl type was only distinguished in official fisheries statistics starting in 1996.

Logbook data

CPUE data were estimated from landed catches and fishing time reported in logbooks for each fishing sequence (succession of hauls performed in the same rectangle with the same gear in a fishing trip). Discards were not available. The catch of the fishing sequences selected for this analysis consists of at least 10% anglerfish (in weight), which corresponds to vessels specialising in anglerfish and some vessels targeting Nephrops. This selection of fishing sequences allows the comparison of fishing efficiency of boats that impact the anglerfish stock significantly. Among the available vessels, we only used data for those having fished every year within the period 1983–1998. The resulting fleet consisted of 25 vessels, which regularly fish anglerfish, and 13 775 fishing sequences.

Explanatory factors are the vessel, its technical characteristics (engine power, age, length, tonnage), the fishing area (ICES subdivision, statistical rectangle), fishing date (day, month and year of the landing), fishing gear (single trawl or twin trawl, information only available from 1996 onwards) and métier. The métier is defined according to the species or the set of species caught and has four categories B (Benthic), D (Demersal), N (Nephrops) and M (Mixed) defined by the following levels of catch for each sequence:

- B if catches of benthic species (anglerfish, rays, megrim) make up at least 20% in weight of total catch,
- D if catches of demersal species (cod, whiting, haddock, ling) make up at least 40% in weight of total catch,
- N if catches of Nephrops make up at least 10% in weight of total catch,
- M: others.

The choice of the levels is the result of cluster analyses on standardised catches in weight and value (Biseau, 1998, Biseau *et al.*, 1999a).

Additional data

Face to face interviews were carried out with the skippers of the 25 selected boats to verify and add information, with particular importance attached to the date of purchase of a twin trawl. This survey was also aimed at obtaining information concerning the temporal evolution of technical characteristics (change in engine power, gear, electronic equipment). Since engine power can change with time, the average over the study period was chosen for the analysis. The number of years when twin trawls were used over the study period was chosen to explain differences between single and twin trawl. Although trawl type was not recorded until 1996, it is important to note that once twin trawls are

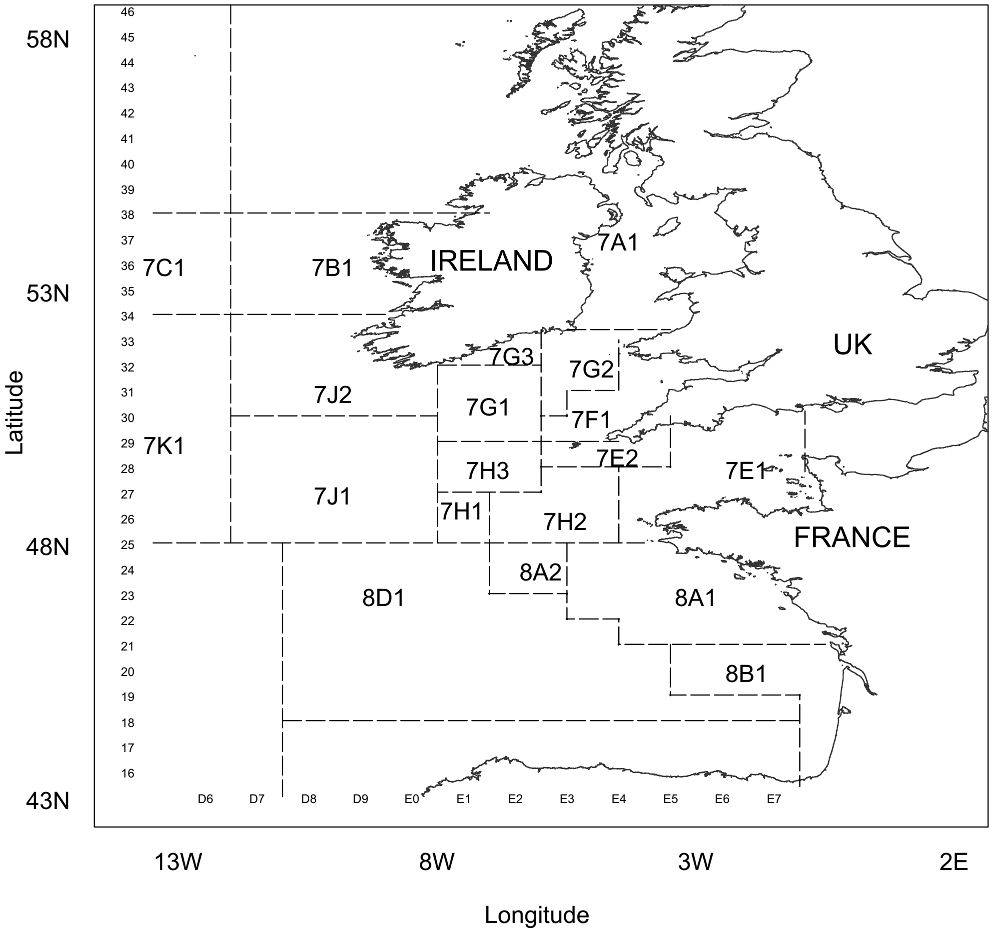

Figure 1. Map showing the fishery area (Celtic Sea and Bay of Biscay) with its subdivisions. Each subdivision is divided into statistical rectangles whose name is given by the concatenation of the associated number on the abscissa and the associated letter–number on the ordinate.

acquired, they are systematically used from then onwards. The survey provided details on the use of GPS, the length of headline, the type of ground rope, and number of years with last skipper (Table 1).

Index vessel

The index or standard vessel was selected in accordance with the following criteria (based on Salthaug and Godo, 2001): (1) constant efficiency and (2) an identical spatial and temporal coverage to one of the fishery. Therefore, to be close to the assumption of constancy of fishing power, the index vessel must have at least no change in technical characteristics: the vessel chosen kept the same engine power and used the same gear during the study period 1983–1998. To minimize the chances of increase in efficiency in catching anglerfish due to skill, we chose a vessel by-catching the species throughout the whole period and we made the assumption that a possible increase in efficiency for its métier may not induce an increase in by-catch efficiency: the vessel's fishing strategy was constant and targeted demersal species, mainly Gadoids. This boat did not actively target anglerfish (724 of 904 fishing sequences with less than 10% anglerfish in catches) but it is able to catch this species when it is present in the fishing area. The index vessel chosen has an important activity in Celtic Sea and Bay of Biscay between 1983 and 1998 (904 fishing sequences) thus providing adequate spatial and temporal coverage over the study period.

Results

An exploratory analysis of logbook data was performed to identify major trends for the study period (Figure 2). The clear decrease in CPUE per year from 1983 to 1991 (Figure 2a) is very similar to the variations in abundance estimated by the ICES assessment working group (ICES, 2002).

Table 1. Characteristics of the technical factors tested in Equation (4): the origin of the information, the description of the variables used to test the influence of this factor on the fishing efficiency, its range and units.

Technical factor	Origin of the data	Construction of the variable	Dispersion of the variable
Engine power	Logbooks	Mean value over the period	211 kW−442 kW
Twin trawls	Interviews	Number of years using twin trawls	(0,…,11)
GPS	Interviews	Number of years using GPS	(6,…,11)
Skipper	Interviews	Number of years with the last skipper	(9,…,16)
Head line	Interviews	Length of the last gear used (×2 if twin trawls)	22 m−56 m
Ground rope	Interviews	Kind of ground rope used	Diabolo, Rockopper or other

It would appear that changes in métier (Figure 2b) could impart marked variability in CPUE of different vessels (Figure 2c), in contrast to the small seasonal variations in CPUE (Figure 2d). Spatial variability (by ICES sub-division) appeared to be very important with large dispersions in the catch rate and an effect on the magnitude of CPUE (Figure 1e). The overall distribution of CPUE observations indicated that a Gamma distribution could be assumed (Figure 2f).

Abundance index

An index of population abundance of anglerfish has been derived from the year effect estimates of the model fitted to

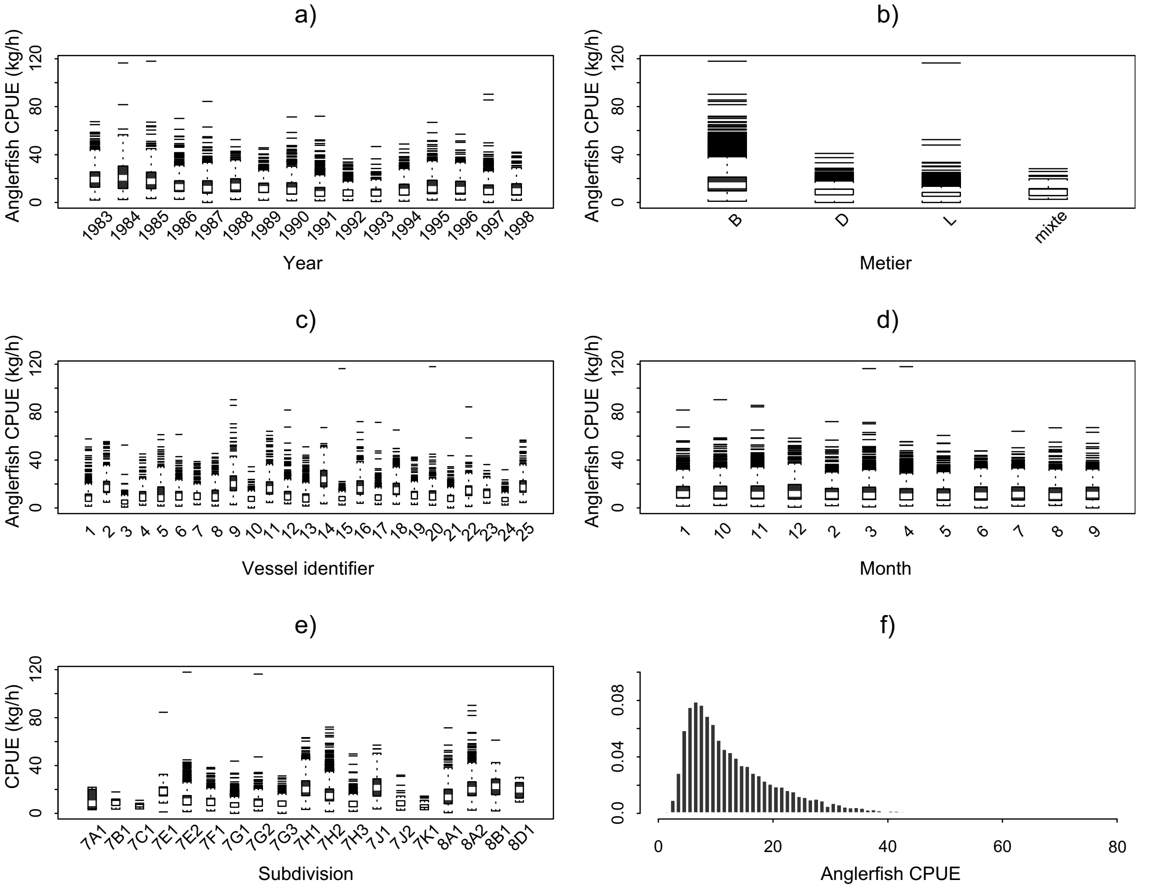

Figure 2. Variability in the median anglerfish CPUE (kg per hour) of the fleet in relation to several variables: (a) year, (b) métier, (c) vessel, (d) month, and (e) subdivision. The whiskers extend from each end of the box to the lowest and highest observation within the intervals defined as 1.5∗(Inter-Quartile Range) below the first and the third quartile. (f) The distribution of the CPUE value.

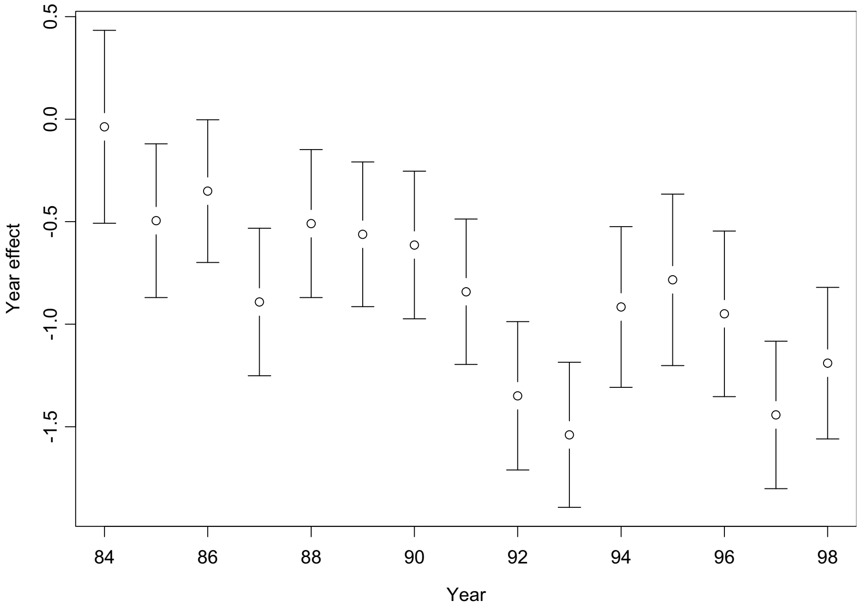

Figure 3. Year effect variations (with 95% confidence intervals) from anglerfish CPUE data for a selected vessel fishing anglerfish as a by-catch (see text, Equation (2)). The reference year 1983 was set equal to 0.

the anglerfish CPUE data of the index vessel (Figure 3). Using the approximate Chi-square test on deviance differences, the model which included all variables gave a reasonable fit (Table 2) and the quality of the fit according to the residual plots (not shown here) indicated that the model explained the variability of the index vessel's CPUE well. We observed a decrease of anglerfish abundance during the period 1983–1998. The period can be separated into three parts showing a similar slope of decreasing abundance, from 1984 to 1987, from 1988 to 1993 and from 1994 to 1998. The highest abundance was observed at the beginning of the period, in 1983–1984 and the lowest in the middle and the end of the period, respectively, in 1992–1993 and in 1997–1998. Good recruitment for *L. piscatorius* in 1989–1993 has led to an increase in the biomass of this species and consequently in the catches since it represents about two-thirds to the total catches.

Overall fleet changes in efficiency

Using the index of abundance calculated above, a GLM (Equation (3)) was fitted to the 13 775 $\mathrm{CPUE_c}$ observations coming from the 25 vessels of the fleet (Table 3). The differences in deviance induced by all main effects indicate a satisfactory fit and the standardised residuals (not plotted here) are consistent with the hypothesis of normality in the light of their linearity against the quartiles of a standard normal law. All main effects were significant whereas none of the interactions between explanatory variables was found to be significant (Table 3). The lack of interactions between the vessel and year variables implies that within the fleet, all vessels had a similar evolution of efficiency over the period. The vessel coefficient shows large differences in the relative average efficiency of vessels during the study period (Figure 4a). Fifty-two percent of the 25 vessels have a fishing power within 10% of the mean. The most efficient vessel of the fleet (vessel 14) had the largest engine power

Table 2. Analysis of deviance of anglerfish CPUE data fitted to calculate an abundance index using an index vessel (from Equation (2)).

	Variable degree of freedom	Variable deviance	Model degree of freedom	Residual deviance	p-Value of Chi-test on deviance
Null			903	588.57	
Year	15	159.59	888	428.98	<0.0001
Month	11	39.42	877	389.56	<0.0001
Métier	1	100.21	876	289.36	<0.0001
Subdivision	15	97.08	861	192.28	<0.0001

Table 3. Analysis of deviance of anglerfish CPUE$_c$ data fitted to estimate fishing power of the whole fleet (from Equation (3)).

	Variable degree of freedom	Variable deviance	Model degree of freedom	Residual deviance	p-Value of Chi-square on deviance
Null			13 772	4956.008	
Vessel	24	1780.359	13 748	3175.650	<0.0001
Year	15	604.412	13 733	2571.238	<0.0001
Month	11	61.926	13 722	2509.312	<0.0001
Métier	3	262.076	13 719	2247.235	<0.0001
Subdivision	18	246.711	13 701	2000.524	<0.0001
Vessel*year	360	346.203	13 541	1654.321	0.69
Year*month	165	95.554	13 176	1558.766	0.999
Métier*subdivision	32	38.449	13 144	1520.318	0.2005

(442 kW). This boat had been using twin trawls since 1988 and had a typical benthic fishing strategy. The least efficient vessel in the fleet (vessel 3) had the lowest engine power (211 kW). Most of the time, this boat was targeting Nephrops and had been using twin trawls since 1994. The métier variable describes the global efficiency of the fleet for each fishing strategy. Compared to the main métier targeting anglerfish (benthic), all other métiers (demersal,

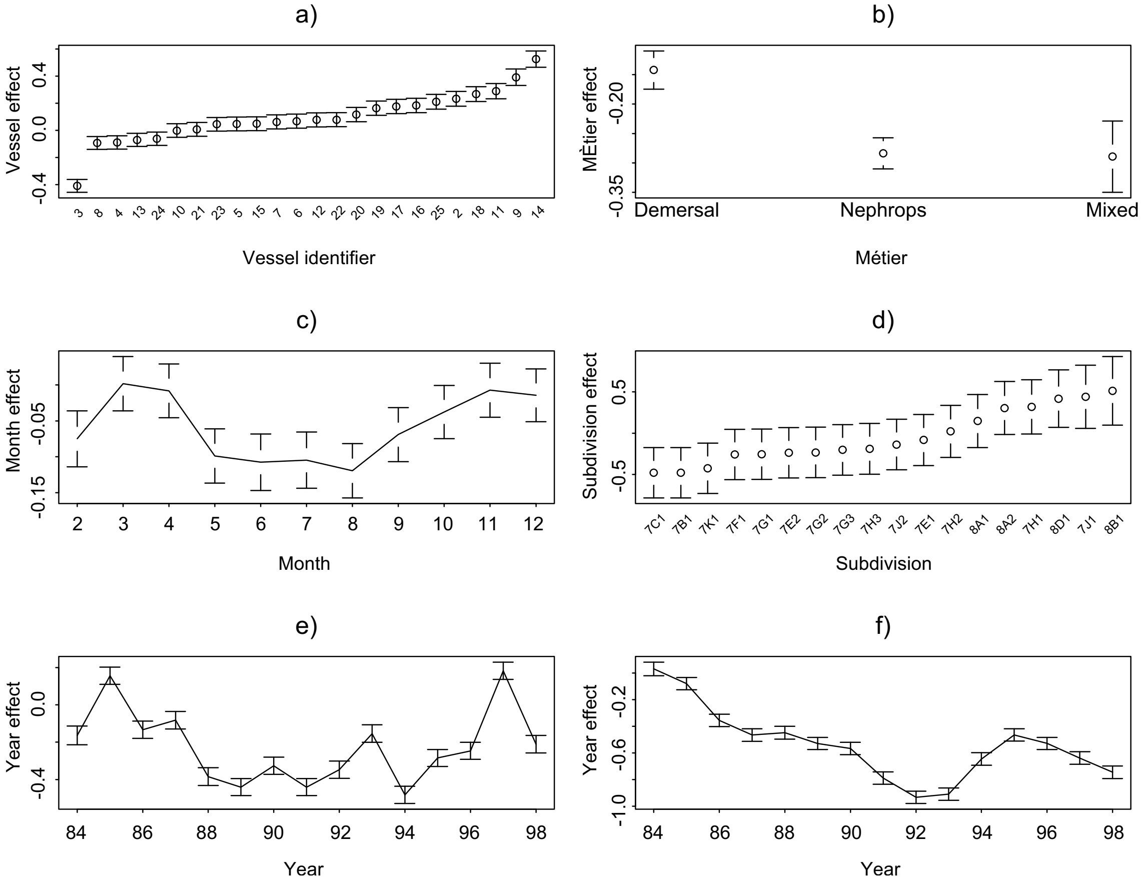

Figure 4. The main effects with 95% confidence interval estimated with the fitted model (Equation (3)) to quantify fishing power. (a) Vessel effect indicates heterogeneity of individual fishing power within the fleet. Vessel numbers on the abscissa are identified by a value from 2 to 25. The reference vessel (1) was set equal to 0; (b) Métier effect. The reference métier (Benthic) was set equal to 0; (c) Month effect. Month on the abscissa is identified by a value from 2 (February) to 12 (December). The reference month (January) was set equal to 0; (d) Subdivision effect. The reference subdivision (7A1) was set equal to 0; (e) Year effect. The reference year 1983 was set equal to 0; (f) Year effect estimated from Equation (3) without filtering CPUE from abundance variations. The reference year (1983) was set equal to 0.

Nephrops and mixed) are, as expected, less efficient (Figure 4b).

The month and the subdivision variables represent seasonal variations in accessibility over the whole study area, and spatial variations in the species distribution over the whole period, respectively. Lower accessibility during spring and summer corresponds to a transfer of fishing effort to Nephrops (Figure 4c). Higher estimates in CPUE for the subdivisions in the Bay of Biscay and the south of the Celtic Sea correspond to a better habitat for anglerfish coupled with a greater accessibility for French trawlers.

The year effect quantifies the annual change in efficiency of the whole fleet over the period. We observed two principal trends in the evolution of the mean fishing efficiency of the fleet (Figure 4e): a period with general decrease from 1983 to 1991 and then a period of general increase from 1992 to 1998 with two breaks in 1994 and 1998. The decrease between 1983 and 1991 (from 0 to −0.5) is only partially recovered by the increase from −0.5 to −0.2 during the period 1992−1997.

To test the relevance of the index vessel to filter the temporal variations in fishing power due to population abundance variations, we compare the annual fishing power estimates of the whole fleet we would have obtained with the CPUE and those obtained with $\mathrm{CPUE_c}$. We fitted a model defined by Equation (3) for the explanatory factors but on the CPUE data instead of $\mathrm{CPUE_c}$ (cf. Table 6). The overall CPUE model has a fit, which is smoother than that of the $\mathrm{CPUE_c}$ model and shows different trends (Figure 4f).

Individual differences in efficiency

A number of factors may explain the large differences in individual vessel efficiency. Engine power has traditionally been put forward (Beverton and Holt, 1954), but in this fishery, a radical change in the fishing method due to the acquisition of twin trawls is thought to be responsible by fishers and managers for an increase of at least 30% or more in efficiency.

We fitted separately six linear models (Equation (4)) to investigate several technical factors which could explain differences in individual efficiency. By order of importance, the most influential technical factors were: engine power, gear type (twin or single trawl) and head line length (Table 4). These results agree well with the fishermen's statements about the causes for the increase in efficiency over the study period. The most common belief was that fishing gear was a key factor in increased efficiency. It explains 29.8% of the variance of vessel efficiency. Availability of electronic equipment (GPS, computers…) was said to improve both comfort and safety of their work rather than fishing efficiency. In this model, it only explained 0.04% of the variance of the vessels coefficients. The number of years of the last skipper had been at the helm (skipper variable in Table 4), did not explain differences in efficiency in contrast to technical factors.

Table 4. Explanation of the differences of efficiency according to technical factors (model from Equation (4). Each row is the result of the fitted linear model associated to the technical factor.

Technical factors	Degrees of freedom	% Variance explained	F-statistic	p-Value
Engine power	22	58.3	30.82	<0.001
Twin trawls	22	29.8	9.324	0.006
Head line	22	27.8	8.453	0.008
Skipper	22	1.9	0.417	0.525
Ground rope	21	0.1	0.011	0.989
GPS	22	0.04	0.008	0.929

Discussion

Unexpected fishing power decrease

The application of a multiplicative model based on $\mathrm{CPUE_c}$ to the South-Brittany bottom-trawlers targeting anglerfish revealed an unexpected decrease in fishing power. From 1983 to 1988, no technical improvement and no tactical change with potential effect on the fleet fishing power were reported in the fishery. Consequently, assuming a constant accessibility, no change in the mean fleet fishing power value or possibly a regular increase due to fisherman skill was expected over this period. Two explanations may explain the decrease in power: (i) the index vessel chosen was inappropriate and did not provide an accurate index of abundance, and thus our approach to provide better estimates of abundance did not perform well; (ii) the fundamental hypothesis of separability (Equation (1)) is not justified and fishing power may be correlated with fish accessibility. It is difficult to choose between the two hypotheses, nevertheless, the model detected a decrease of fishing power from 1985 to 1991, followed by an increase thereafter. Given that the use of twin trawls had started in the late 1980s (Table 5) and that gear change explains 30% of the fishing power variability (Table 4), this feature might reveal a temporary period of adjustment to new equipment until 1991. The recovery in fishing power after 1991 can be explained by a progressive acquisition of twin trawls by the fleet over the period (Table 5). Between 1991 and 1997, fishing efficiency for anglerfish increased by approximately 10% annually (Figure 4e).

Technical explanations of differences in fishing power

Although engine power appears to explain the greatest portion of the variation (Table 4), this result must be taken with great caution because of some unreliable engine power declarations. Skipper skill was expected to explain more of the differences than quantified by the model. The low influence on explained variance can be interpreted as indicating that experience acquired by fishermen on

Table 5. Annual evolution of total number of vessels getting twin trawls or GPS within the fleet.

	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998
Twin trawls	0	2	4	6	6	7	8	9	10	10	11	13
GPS	0	2	16	21	21	24	25	25	25	25	25	25

average has less influence on increased efficiency than the purchase of a new equipment.

Model hypotheses

Classical studies of fishing power make the assumption of a homogeneous distribution of the species and a homogeneous fishing power over the whole fishing area. The significance of the spatial effects in Equations (2) and (3) (Tables 2 and 3) suggests that this assumption may not be valid. Until 1986, fishermen have declared catches and effort using the ICES subdivisions, however after 1986 declarations were required at the level of ICES statistical rectangles. Consequently, to model the whole period, the ICES subdivision was used as the spatial scale in Equation (3), making an assumption of CPUE homogeneity within each ICES subdivision. To test this assumption, two models (Equation (3)), one with the ICES statistical rectangles as spatial explanatory variable and another with the ICES subdivision, were fitted over the period 1986–1998. In light of the values of the AIC (the lowest is obtained with the rectangle 9445.5 against 10189.7 for the subdivision and against 11578.12 without any spatial covariate), the assumption of CPUE homogeneity within ICES subdivisions is probably incorrect. However, ICES rectangles are certainly still too large to take into account the real local heterogeneity (variation in depth, temperature, substrate, etc.).

Previous attempts to evaluate and characterise fishing power have taken into account trends in fishing power: the year effect describing the annual change in catch rates not only quantifies the change in efficiency but also reflects changes in abundance. In order to separate the annual variations in abundance from the trend in fishing power, we have transformed the CPUE data according to an annual index of abundance. This index had to be independent of CPUE data currently used by the ICES Working Group on the Assessment of the Southern Shelf Demersal Stocks. Harley *et al.* (2001) used research survey abundance estimates from a vessel with no trend in fishing efficiency and with a spatial and temporal coverage consistent with the commercial fishery to have fishery-independent estimate of abundance. The French trawl surveys EVHOE would have seemed *a priori* the most appropriate survey with our study. However, the low abundance of anglerfish in catches, radical changes in the spatial coverage of the survey and discontinuous monitoring over time, led us to prefer the use of an index vessel from the fishing fleet.

Our approach is reliant on the assumption that the index of population abundance estimated from CPUE data of the index vessel is proportional to true abundance if the index vessel has at least a constant fishing efficiency (Salthaug and Godo, 2001). To ensure a constant fishing efficiency, we selected a vessel that has no change in technical characteristics and did not target anglerfish. However, these criteria might have not been sufficient: an increase in skipper skill could have increased its fishing efficiency for another species and then indirectly resulted in a change in fishing efficiency on anglerfish.

The use of a single index vessel might be considered a constraint of our approach and it would have been better to have a fleet of such standard by-catch vessels in order to integrate the individual variability in by-catching anglerfish in the estimated index of abundance. With regard to difference in trends in year effect between the models (3) fitted on CPUE_c (Figure 4e) and on CPUE (Figure 4f), use (and hence choice) of the index vessel has an impact on the estimation of the annual changes in fishing efficiency. Without filtering CPUE data from the annual variations of abundance, the fishing power estimates (Figure 4f) detected more variations in abundance (Figure 3) than changes in fishing efficiency (Figure 4e). This can be explained by

Table 6. Analysis of deviance of model describing the monkfish CPUE inside the whole fleet (without filtering CPUE from abundance variations).

	Variable degree of freedom	Variable deviance	Model degree of freedom	Residual deviance	p-Value of Chi-test on deviance
Null			13 774	5417.74	
Vessel	24	1685.41	13 750	3732.33	< 0.0001
Year	15	1099.09	13 735	2633.23	< 0.0001
Month	11	63.09	13 724	2570.15	< 0.0001
Métier	3	265.44	13 721	2304.71	< 0.0001
Subdivision	18	243.45	13 703	2061.26	< 0.0001

a lower impact of changes in fishing power on CPUE variations of anglerfish than changes in anglerfish abundance. Nevertheless changes in fishing power make CPUE data of vessels targeting anglerfish not exactly proportional to population abundance. In stock assessment models, "tuning fleets" of vessels targeting the species of interest are used to estimate fishing mortality, and rely on the assumption of proportionality. Our results indicate that using such vessels' CPUE data without estimating changes in fishing efficiency might lead to over-optimistic estimations of the stock. Two solutions could be considered: either the input data are filtered for changes in efficiency, or the only relevant "tuning fleet" is based on vessels that show no changes in fishing efficiency over time.

Modelling approach

Most studies that attempt to explain differences in efficiency with technical characteristics directly introduced the explanatory variable in the general model (for instance, Hilborn and Walters, 1992; Gaertner *et al.*, 1996; Gillis, 1999; Rijnsdorp *et al.*, 2000). The reasons for our two-step approach (models from Equations (3) and (4)) are twofold. First, the causes of variations in the CPUE data are very complex. The decomposition allowed filtering out of the spatio-temporal and strategic variations from catch rates and to thereby concentrate on variability associated with technical differences. Second, we wanted to quantify the change in fishing power of each vessel in the fleet that requires a vessel identifier in GLM (Equation (3)). In this model, some technical variables in addition to the vessel identifier might have been considered, but the high correlation between the resulting explanatory variables would have induced a singular model-matrix leading to impossible or non-unique solution (Draper and Smith, 1998). Integrating a technical variable and removing the vessel identifier in Equation (3) allows quantification of the fishing power associated with this variable for the whole fleet. In the context of a multi-species fishery, fishing power would not easily be reduced to a single technical variable.

Data quality

More precise results might be achieved if the quality of the input data was improved. For instance, the length of head line was only available for each vessel in the most recent year. Therefore, its inclusion in the analysis (Equation (4)) assumed its constancy over the whole period. The use of a mean weighted by the number of years using each gear may have been more suitable. The length of head line can be used as a proxy for the area trawled by a boat. It would also be interesting to consider the volume trawled, which depends on the speed of trawling and on the rigidity of the mesh. The rigging of the gear, which was not available for our study, may also be an important element to consider because fishermen repeatedly pointed out that appropriate rigging can compensate for differences in engine power. In face to face surveys, many questions (e.g. dates of acquisition of new equipment) were subject to qualitative interpretation on the part of each skipper. This uncertainty surrounding answers of fishermen could be reduced through better record keeping by industry or authorities. Using CPUE for each haul instead of CPUE by fishing sequence should also improve the fishing power estimates. A fishing sequence is composed of several fishing operations, which can be directed to different species in different ways. However, CPUE by fishing sequence is assigned to a particular métier, assuming that fishermen have not changed in métier during a fishing sequence.

Future research

The approach developed in this paper allows characterisation and quantification of the differences in efficiency within the fleet and annual quantification of variations in mean fishing power for the whole fleet. Equation (4) quantifies the influence of technical factors on mean fishing efficiency of the whole fleet. The same process may be applied to each boat taken individually, fitting Equation (3) to each boat's data set. Such an approach is particularly interesting when vessel–year interactions in Equation (3) are significant, suggesting that fishing efficiency of vessels does not change in the same way. According to comparisons between estimated coefficients when interactions are significant (Philippeau, 1989), the evolution of fishing power inside the fleet can be studied vessel by vessel and comparisons between vessels can only be made in a given year. Annual variations in fishing power of a single boat could then be compared with its annual variations in technical or human factors.

One of the most important results of our approach is that it provides the estimation of annual values of fishing power for the fleet. These annual values must be seen as conversion factors between nominal effort (main parameter for fisheries management) and effective effort, which is representative of fishing mortality. Such a conversion factor could be the link between stock assessment and fisheries management. Most of the assessment models use fishing effort or CPUE data either directly (surplus production model) or to tune the analysis (e.g. XSA or sequential population analysis). Such use of nominal effort could lead to inaccurate estimates of variation in abundance because an increase in efficiency may be interpreted as an increase in abundance.

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