**ICES CM 2005/V:01**

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# The influence of market and fish stocks density on fishers' foraging

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## ABSTRACT

This study has investigated the spatial structure of fishing effort distribution and also, using Levy flights theory, some properties of fishermen's foraging. The case studies examined were a selection of North Sea Dutch and French vessels, for which catch and effort data were collected on a haul-by-haul basis. A 3x3 nautical miles observation window could be reasonably appropriate to carry out investigations on fleet behavior. Foraging behavior may reasonably be represented by a Levy flight process. Efficient foraging led to high catch rates, while the knowledge of fishing grounds with high stock density is shown to increase foraging efficiency in the short-term future. The absence of correlation between the French vessels' foraging and saithe price was less expected. It could be explained by the limited span of the time series being analysed and/or the fact that there are only limited alternatives to saithe fishing for the fleet being investigated.

## KEYWORDS

Fleet behavior, Levy flights, fishing effort, foraging, haul-by-haul data,

## INTRODUCTION

The effectiveness of fisheries management relies heavily on the understanding of a number of key processes including fishers behavior, technical creeping and the impact exerted by fishing units on the ecosystem. Changes in fishers' behavior have been demonstrated in a number a studies, with regards to shifts in either the spatial distribution of fishing effort (Rijnsdorp et al. 1998, Rijnsdorp et al. 2000a), or métiers choices (Holley and Marchal 2004, Ulrich and Andersen 2004), or discarding practices (Stratoudakis et al. 1998). The effect of fishers' behavior on catch rates has been investigated by, e.g., Abrahams and Healey (1980), Hilborn (1985), Sampson (1991), Gillis (1999), Salthaug and AAnes (2003). Other studies have examined the different factors which could influence fishers' decisions. The factors investigated included the fishers' perception of stock density (Hilborn and Ledbetter 1979, Gillis et al. 1993, Hutton et al. 2004), management regulations (Pascoe et al. 2001, Marchal et al. 2002), competition between fishing vessels (Gillis and Peterman 1998, Rijnsdorp et al. 2000b) and fish prices (Holley and Marchal 2004). These processes have to some extent been integrated into prototype simulation models, which have been developed to represent the dynamics of fishers' behavior (Dorn 1997, Holland 2000, Salas et al. 2004). Despite these advances, a substantial amount of work still has to be carried out to get a more comprehensive understanding of the complexity underlying fleet dynamics, and to be able to include the key processes into an operational bio-economic model, which could be used routinely by fisheries managers.

One of the areas where progress could be made is in the definition of indices describing fishing tactics and strategies in an appropriate way. Building on the ecological theory, such indices have already been used to describe fishers' behaviour. For instance, the spatial distribution of fishing effort has been characterized by either the Shannon-Wiener diversity index (Abrahams and Healey 1990), or the distance covered by fishing vessels (Salthaug and AAnes 2003), or coefficients of patchiness (Rijnsdorp et al. 1998, Salthaug and AAnes 2003). More recently, other indices have been considered in the ecological literature to characterize the spatial distribution of predators or foragers. One of these approaches builds on the Levy flight theory to characterize how efficient foragers are in looking for sparsely and randomly distributed targets (Viswanathan et al. 2002). This theory has been successfully tested on different foraging animals such as bees (Viswanathan et al. 1999) and wandering albatrosses (Viswanathan et al. 1996). More recently, this approach has been applied to describe the fishers' searching behavior in the Peruvian anchovy fishery (Bertrand et al. 2005).

The scope of this paper is, (i) to identify spatial structures in the fine-scale spatial distribution of fishing effort, (ii) to characterize the foraging efficiency of these vessels based on the Levy flight theory and, (iii) to get better insight into the factors which may impact the fishers' foraging. This approach was applied on two case studies, for which fine scale, haul by haul, catch and effort data could be made available: the Dutch large beam-trawlers targeting sole (*Solea solea*) and plaice (*Pleuronectes platessa*), and the French large otter-trawlers targeting saithe (*Pollachius virens*).

# MATERIAL AND METHODS

## Data

*Dutch fleet*

The Dutch fleet investigated includes large beam-trawlers (>300 HP). The target species of these fleets are plaice and sole and the fishery takes place throughout the North Sea. Beam trawl vessels usually fish from Sunday night until Friday morning. They fish throughout day and night and need about 15 minutes for emptying the nets and setting the nets back into the water. During the weekend most of the vessels are in the harbor, although a small group of vessels sometimes go out to see for a 2-weeks trip. Haul-by-haul logbook data are compiled, containing landing, mid positions and timing of each haul (Table 1). Fishing grounds of the Dutch fleet under investigation are situated throughout the North Sea, but outside of the 12-miles zone, where these vessels are not allowed to fish (Figure 1). Most of the effort registered in the haul-by-haul data is located in the southern part of the North Sea.

*French fleet*

The French fleet investigated includes large otter-trawlers (>40 m) registered in Northern France. This fleet is sub-divided into two groups of vessels. The first group of vessels operates mostly in the Northern North Sea and targets saithe. The second group operates off Western Scotland (sub-area VI) and in the Celtic Sea (sub-area VII), and targets deep-water species. Only the haul-by-haul catch and effort data provided by the first group of vessels were collected. However, these data were collected for most of the fishing trips operated by these vessels (Table 1). Fishing grounds of the Northern France otter-trawlers are mainly situated in the Northern North Sea around the Shetland Islands (Figures 1).

*Fish prices*

Monthly fish prices were made available from sale slips for sole and plaice, harvested by the Dutch fleet, and for saithe, harvested by the French fleet.

## Methods

### Spatial structures in the distribution of fishing effort

The issue here is to evaluate up to which spatial resolution the distribution of fishing effort becomes random, and the methodology is derived from Rijnsdorp et al. (1998).

First, the number of hauls is aggregated over spatial observation windows of different resolution:

*a)* 30’ latitude x 60’ longitude (≡ 1 ICES rectangle, i.e. the same resolution as in EFLALO)

*b)* 10’ latitude x 20’ longitude (≡ 1/9 of an ICES rectangle)

*c)* 03’ latitude x 06’ longitude (≡ 1/100 of an ICES rectangle)

*d)* 01’ latitude x 02’ longitude (≡ 1/900 of an ICES rectangle)

Second, the cumulative plots of ranked dispersion coefficients $C = s^2/\mu$, where $s^2$ and $\mu$ are the variance and mean of the number of hauls calculated over the fishing areas characterized by a) – d). Values of 1 indicate that the distribution of fishing effort is random. When $C > 1$, the spatial distribution of fishing effort is patchy.

Third, the user identifies and records the spatial resolution (a), b), c) or d)), at which fishing effort may be considered as randomly distributed (i.e. $C \approx 1$ for 95% of the spatial units).

**Quantifying the foraging efficiency of the fishing fleets**

The concepts underlying this analysis are based on the Lévy flights theory, and they may be found in Viswanathan et al. (1996, 1999, 2002). Lévy flights are characterized by a distribution function

$$P(l_i) \sim l_i^{-\mu}$$

with $1 < \mu \leq 3$, and where $l_i$ is the flight length, which in the present analysis is interpreted as the distance covered by a fishing vessel between two fishing operations. The gaussian is the stable distribution for the special case $\mu > 3$, while values $\mu \leq 1$ do not correspond to probability distributions that can be normalized. Value $\mu$ = 2 characterizes an optimal foraging search.

To estimate the parameter $\mu$, one proceeds as follows. For each fleet and each month, the frequency distribution of the distance between hauls ($l$) is calculated. The bin size used to group the continuous variable $l$ into discrete classes is that suggested by Scott (1979). Log-frequency is then plotted against Log($l$), using the arithmetic mean of the bins. A regression is then fitted through the data points, the slope of which is - $\mu$. Monthly time series of $\mu$ are thus produced for each fleet, and their temporal structure is examined using an auto-correlation function.

**Factors affecting foraging**

Monthly time series of the foraging parameter $\mu$ were contrasted with catch rates (or CPUE) and fish prices time series. The species for which these variables are calculated are sole and plaice (Dutch fleet) and saithe (French fleet).

When $\mu$ is close to 2, foraging is expected to be optimal, and catch rates should be higher than average. Catch rates could also be used as an indicator of fishers' perception of stock density. It is likely that fishers adapt their fishing strategy as a result of the yield they achieved in past month(s). Therefore, past catch rates may have an influence on their foraging behavior, and hence on $\mu$.

Past fishing efforts could be seen as a proxy for experience, which could benefit to foraging efficiency. The relation between the foraging parameter and fishing effort was therefore investigated.

Price fluctuations make a target species attractive or not. It is therefore likely that $\mu$ will depend on market conditions, as reflected by fish prices.

Finally, although management has an impact on fishers' behavior, it has not been integrated in our analysis. The Dutch fleet is constrained both by the plaice and sole TACs (Total Allowable Catches) and also by effort limitations taken in the North Sea to restore the cod (*Gadus morhua*) stock. However, these management measures have not changed during the period investigated (2003). Regarding the French fleet, the saithe TAC is not constraining, and the fleet has been little affected by the measures taken in the North Sea to restore the cod (*Gadus morhua*) stock. Therefore, the effect of management is believed to be either constant (Dutch fleet) or negligible (French fleet), during the period investigated.

A cross-correlation function was used to quantify the linkage between the foraging parameter $\mu$, catch rates, fishing effort and fish prices, at different time lags.

### Implementation

The different analyses detailed above have been implemented using mainly SAS/STAT (1999) and SAS/ETS (1999).

## RESULTS

### Spatial structures in the distribution of fishing effort

Overall, the distribution of the Dutch beam trawlers appears to be more patchy than that of the French otter trawlers, irrespective of the spatial resolution of the observation window (Figures 2a and 2b). With the 1x1 nautical miles window size, fishing effort may be considered as randomly distributed (i.e. coefficient of dispersion lower than 1) for 20% (respectively 50%) of the spatial units harvested by the Dutch vessels (respectively the French vessels). With the 3x3 nautical miles window size, that proportion increases up to 80% for the Dutch vessels, and 95% for the French vessels. With the 1x1 nautical miles window size, fishing effort may be considered as randomly distributed for almost all the spatial units being exploited.

**Quantifying the foraging efficiency of the fishing fleets**

Two examples of the log-log regression between frequencies and inter-haul distances are given on Figures 3a (Dutch fleet) and 3b (French fleet). The slope of the log-log regression between frequencies and inter-haul distances was always significantly different from zero ($p < 0.01$), except for the French fleets in October, November and December 2003, due to few data points (Figures 4a and 4b). In these three cases, the foraging parameter $\mu$ was set to zero. In all other cases, $\mu$ was set to minus the slope of the regression. The foraging coefficient $\mu$ oscillates within [1.5-1.9] for the Dutch fleet. For the French fleet, $\mu$ fluctuates within [1.2-1.8], except during the period October-December 2003, where this coefficient was set to zero, as explained above.

We find that $1 < \mu \leq 3$ in most of cases, suggesting that the distance covered by a fishing vessel between two fishing operations may reasonably be represented by a Levy flight process. For the Dutch fleets, the value of $\mu$ was not significantly different from 2, which characterizes an optimal foraging search, for most of the time period except in the summer (between July and September 2003). For the French fleet, foraging was closest to optimal (i.e. $\mu$ not significantly different from 2) in May, August and September 2003 and in April and June to September 2004.

The auto-correlation of the French fleet's foraging parameter is significant at lag 1 only, which characterizes a purely auto-regressive (or random walk) process (Figure 5b). A similar process underlies the dynamics of the Dutch fleet's foraging parameter. For this fleet, there is also a significant auto-correlation at lag 4, but this can hardly be interpreted, given the limited span of the time series.

**Factors affecting foraging**

Consider the correlation between $\mu$ and catch rates. For the French fleet, high saithe catch rates are generally achieved when $\mu$ is close to 2 (Figure 6b), which is also reflected by a significant cross-correlation between the two time series at lag 0 (Figure 7b). In addition, high catch rates positively impact the foraging efficiency one or two months later (Figure 7b).

Consider the correlation between $\mu$ and fishing effort. For both fleets, high levels of fishing effort are associated with efficient foraging (Figures 6c, and 6d), which is reflected by significantly positive cross-correlations at lag 0 (Figures 7c and 7d). There are also significant cross-correlations (positive or negative) between the two series at different lags for (Figures 7c and 7d).

Consider the correlation between $\mu$ and fish price. For the French fleet, the saithe market price does not appear to be correlated with foraging efficiency, whatever the time lag considered (Figures 6f and 7f).

## DISCUSSION

The patchiness of the fleets' distribution may reflect to some extent the distribution of the target species (Salthaug and AAnes 2003, Bertrand et al. 2005). This may indicate that the distribution of saithe is more scattered than that of flatfish in the North Sea. Another important corollary of the investigation on the spatial structures in the distribution of fishing effort is the confirmation that the ICES rectangle, the size of which is 30x30 nautical miles, is clearly an inappropriate spatial scale for studying fleet behavior. The results also suggest that, for both fleets, a 3x3 nautical miles observation window could be reasonably appropriate to carry out that type of investigations.

The analysis of foraging efficiency suggested that, for the fleets under investigation, the foraging strategy may reasonably be represented by a Levy flight process. High catch rates were generally achieved when foraging was close to optimal, as expected. The link between past catch rates and current foraging efficiency may result from catch rates refleting the fishers' perception of stock density. Thus, high catch rates could be expected to benefit the skippers' experience in terms of knowledge of fishing grounds with high stock density. It may then be anticipated that this gain in experience could contribute to increase foraging efficiency in the short-term future (i.e. one or two months later for the case studies under investigation). Efficient foraging was also associated with high levels of fishing effort, which is a reasonable result. However, the linkage between fishing effort and past or future foraging efficiency was more complex, and could not be interpreted with the series available. The absence of correlation between the French vessels' foraging and saithe price was not expected. Holley and Marchal (2004) have shown that the decline of saithe prices over the period 1999-2003 have made saithe fishing gradually less attractive over that period. The reason why such a result could not be confirmed here is probably that the time series was of a relatively limited span (April 2003 – September 2004) and that the decrease of the saithe market price was more moderate over that period. Another reason is that the French saithe fishery is a single-species fishery. When saithe fishing is not economically attractive, the fishery can hardly move towards alternative target species. The only option may then be to stop fishing for a spell, which is actually what happened to several vessels of that fleet between October and December 2004.

This study examined some of the key processes underlying fishers' behavior. Management was not identified as a key factor, given the size of the time series being analysed. With longer time series (which are expected to become available via VMS data recording and observers on-board) the span of these series will increase. Management would then become a key factor to be examined along with economic parameters and skippers' perception of fish density. Longer time series will also permit to carry out modeling exercises (e.g. ARIMA, Kalman filtering), which may help forecasting fleets' behavior in the short-term future.

## ACKNOWLEDGEMENTS

This work was funded through the TECTAC project by the European Union (DG Fisheries, study no. QLRT-2001-01291). This support is gratefully acknowledged. We are also indebted to skippers and vessels owners for providing data, without which this investigation could not have been carried out.

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**Table 1.** Monthly number of vessels, fishing trips and fishing operations collected and used to provide landings and effort inputs to the present analysis.

| Fleet | Period investigated | No. vessels per month | No. trips per month | No. hauls per month |
|---|---|---|---|---|
| Dutch beam trawlers | January 2003 – December 2003 | 6-8 | 14-36 | 44-84 |
| French otter trawlers | April 2003 – September 2004 | 1-4 | 2-7 | 10-31 |

**Figure 1.** Map of the investigated ICES (International Council for the Exploration of the Sea) areas, including the spatial distribution of fishing effort in 2003 for the sample of Dutch large beam-trawlers and French large otter-trawlers, for which haul by haul catch and effort data were available.

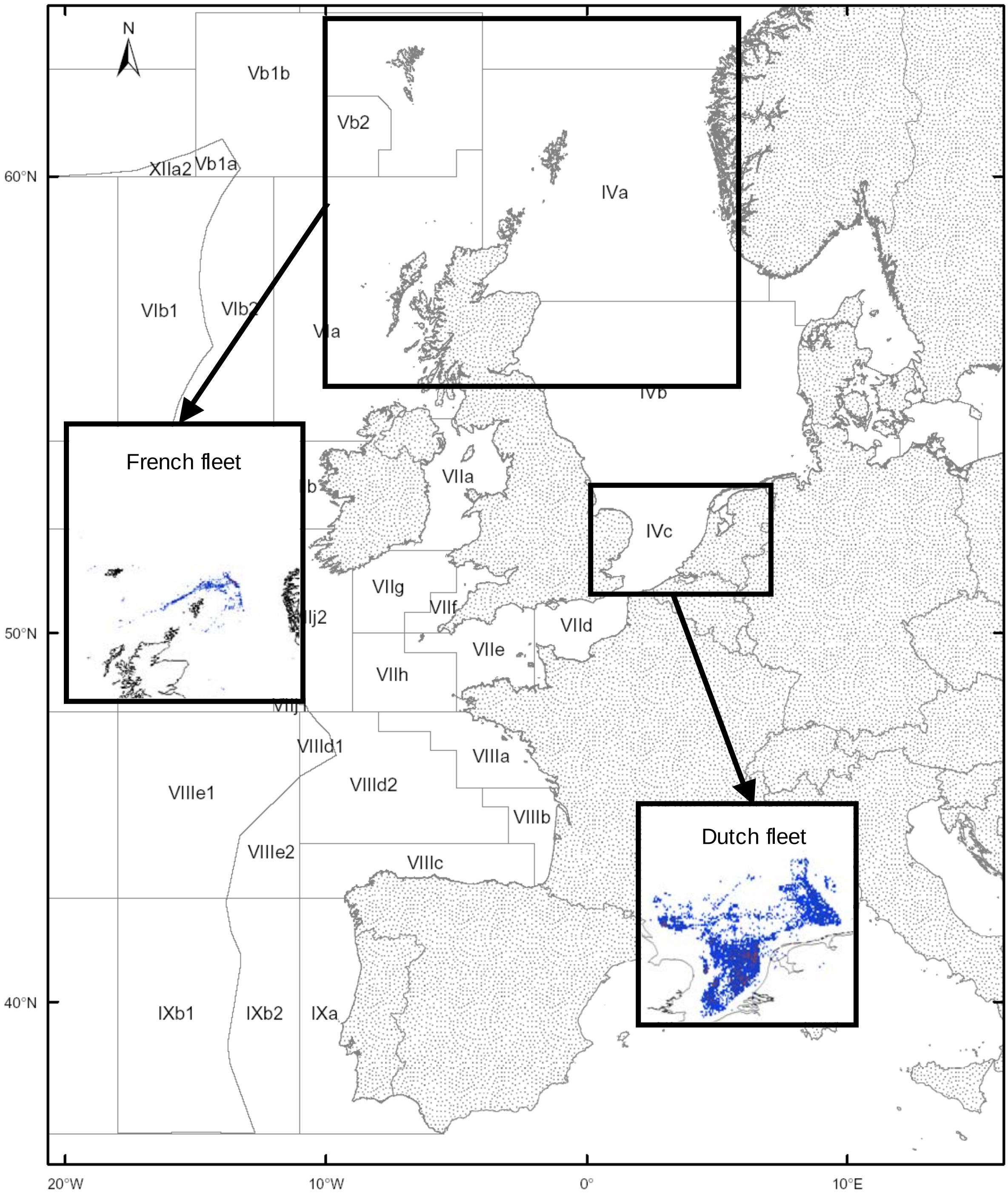

**Figure 2a.** Dutch large beam trawlers. Relationship between the surface area fished and the ranked coefficients of dispersion, for different spatial resolutions.

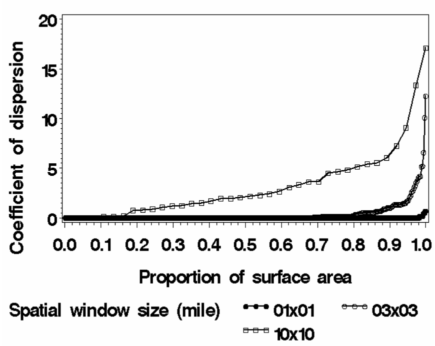


**Figure 2b.** French large otter trawlers. Relationship between the surface area fished and the ranked coefficients of dispersion, for different spatial resolutions.

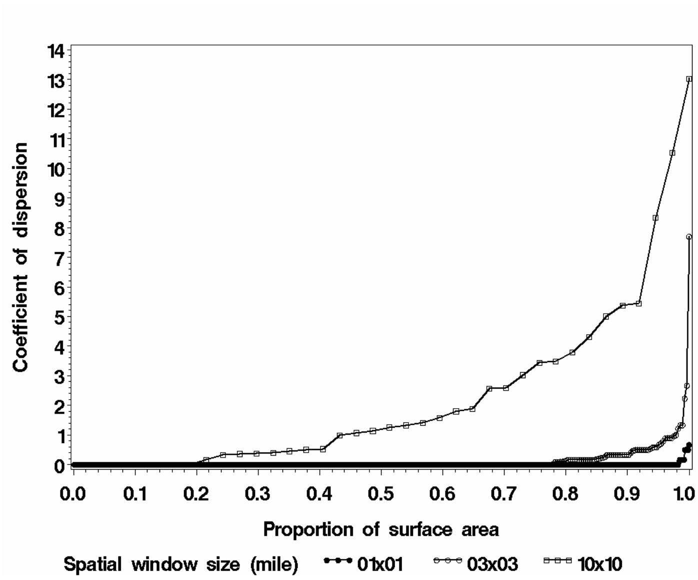

**Figure 3.** Regression, on a log-scale, of the frequency distribution of the distance covered by a fishing vessel between two consecutive hauls (Y axis) versus that distance (X axis). The slope of the regression is - $\mu$. Examples (one month and one fishing vessel) drawn from (a) the Dutch fleet and (b) the French fleet.

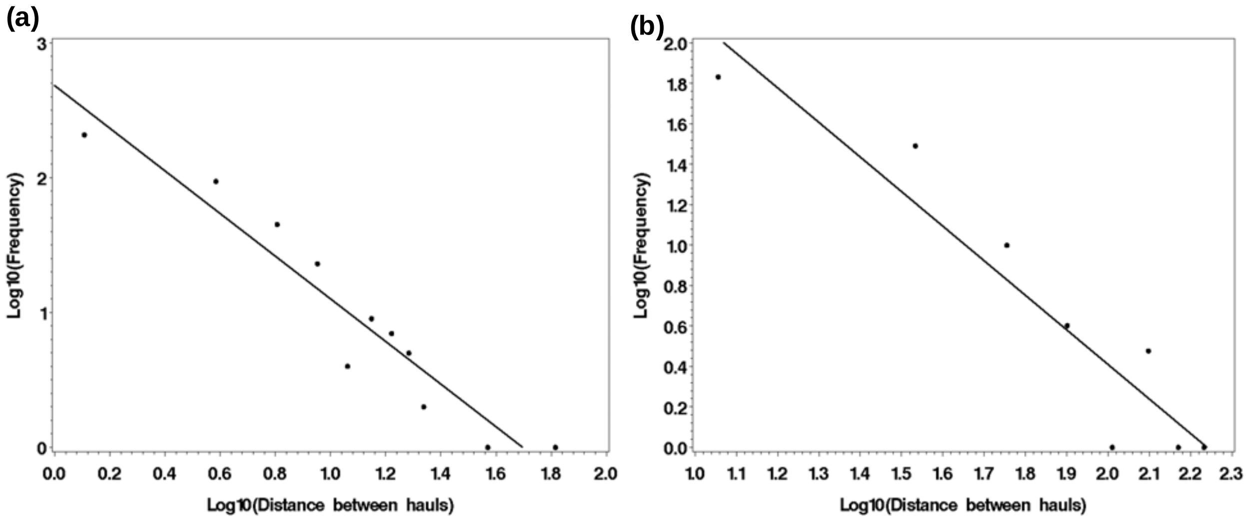

**Figure 4.** Time series of the foraging parameter $\mu$ (black dot), including 95% confidence limits intervals (dotted lines), as calculated for (a) the Dutch large beam trawlers and (b) the French large otter trawlers.

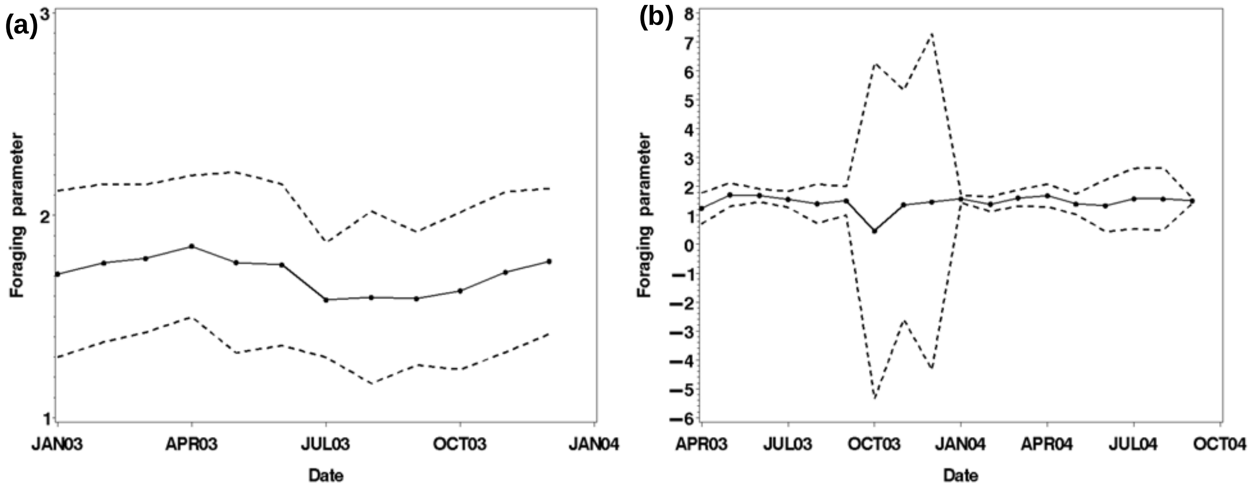

**Figure 5.** Auto-correlation of the foraging parameter $\mu$ (needles), and standard error based on the hypothesis that the process generating the time series is a pure moving average (dotted lines). Case studies investigated are (a) the Dutch large beam trawlers and (b) the French large otter trawlers registered in Northern France.

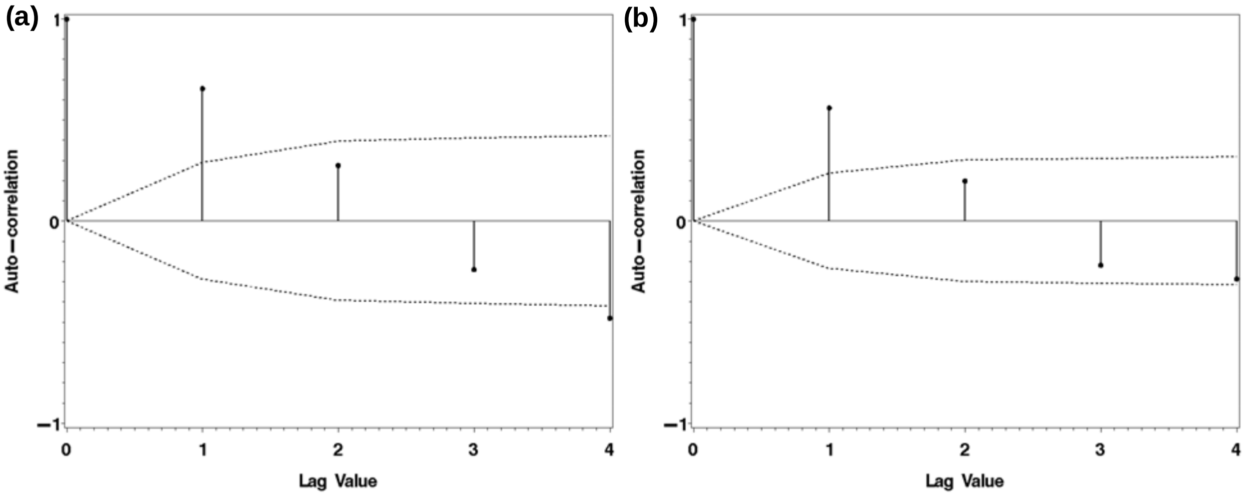

**Figure 6.** Time series of the foraging parameter $\mu$ (black dot), combined with time series of, (a) sole (*Solea solea*) and plaice (*Pleuronectes platessa*) catch rates (kg/hour fished), (b) saithe (*Pollachus virens*) catch rates, (c, d) fishing effort (hours fished), (e) sole and plaice prices, (f) saithe prices. Case studies: (a, c, e) Dutch large beam trawlers and (b, d, f) French large otter trawlers registered in Northern France.

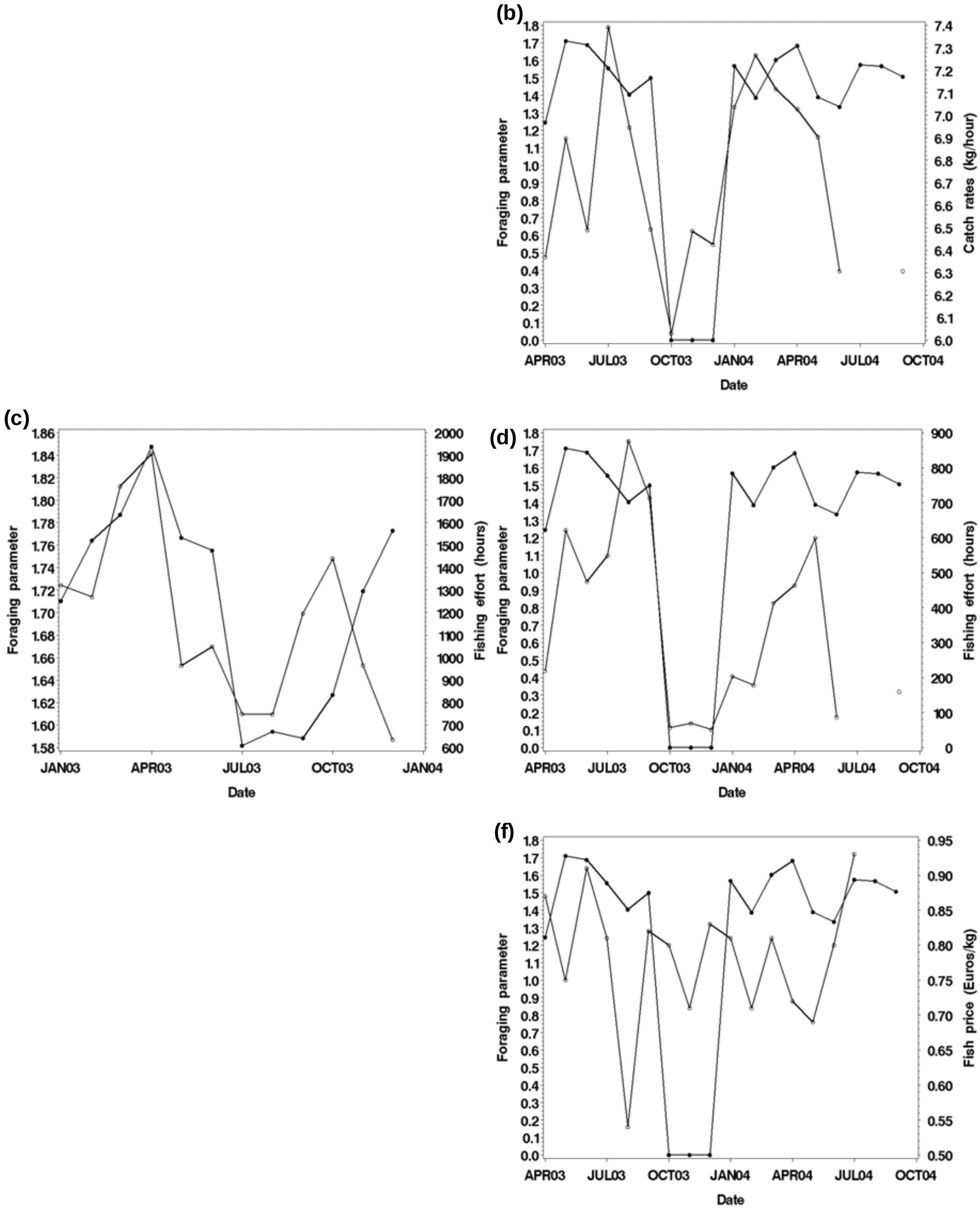

**Figure 7.** Cross-correlation (needles) of the foraging parameter $\mu$ with, (a) sole (*Solea solea*) catch rates, (b) saithe (*Pollachus virens*) catch rates, (c, d) fishing effort, (e) sole price, (f) saithe price. The standard error under the assumption that two time series are uncorrelated is represented as dotted lines. Case studies investigated are (a, c, e) the Dutch large beam trawlers and (b, d, f) the French large otter trawlers registered in Northern France.