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Persistence of acoustically observed fish biomass in a 220 km^2 survey region

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ABSTRACT

Short-term harvest refuges have attracted the interest of fisheries managers as a means to protect juvenile fish. Implementation would require fishermen to report high catch rates of juveniles in a small area, whereupon the area would be closed to fishing for a specified period, perhaps two weeks. In this way, the juveniles are protected in the short-term, but fishing grounds remain available to the fleet in the long-term. Naturally, such management makes assumptions about the persistence of juvenile fish in the harvest refuge. We consider how to design a survey whose primary objective is to address spatial persistence. Acoustic surveys are particularly suited to this question, and we describe the design and analysis of acoustic survey data collected over a 220 km^2 survey region off the coast of Yorkshire. We employed generalized additive models to investigate space/time interactions and to partition temporal variation into diel and persistence components. We also consider how trawl catch can supplement the acoustic survey. Finally, we demonstrate visual data analysis techniques that provide a summary of fish behaviour in the region. Our analysis suggests that the total biomass in the area could fall by as much as 50% in a period of three days. We take this to indicate that larger areas would be required for effective protection of young fish.

Keywords: fisheries, generalized additive modelling, refuges, temporal persistence

INTRODUCTION

It has long been understood that one of the most effective means of protecting fish stocks is to allow many of the fish to reproduce at least once (c.f. Cushing, 1975). Not only does this aid future recruitment, it typically allows the fish to reach a profitable size. Fisheries management has traditionally relied upon the indirect technical measures, such as regulation of mesh sizes, to protect juvenile fish. By allowing the smaller fish to pass through the fishing nets, these regulations have often met their objective. Still, mesh size regulations have their drawbacks: meshes can become clogged on longer tows, preventing escape, or juvenile fish can be injured passing through the gear, leading to mortality that is difficult to account for in stock assessment. These and other difficulties have led to an investigation of harvest refuges as an additional means of protecting juvenile fish (Roberts and Polunin, 1993; Schmidt, 1997; Watson, 1997).

Wherever juvenile fish are separated from the adults, a feature encountered in many species, area closures have the potential to protect the immature individuals. Indeed, if permanent nursery grounds can be identified, closing these to fishing at appropriate times might be an effective fishery regulation (c.f. Horwood *et al*., 1998). The use of permanent harvest refuges or marine reserves in this situation is developing a large literature. In general, however, it would not be surprising if some fish stocks maintained a separation between juveniles and adults without tying the juveniles down to a fixed site. For such stocks, permanent harvest refuges would not provide effective protection for the young fish and could lead to a false sense of security. Effective protection might be achieved with short-term closures of a few weeks, set up in response to high juvenile catch rates in the fishery. While such short-term closures would certainly pose logistical challenges, their use has attracted interest within the ICES (International Council for the Exploration of the Sea) community. As with any area closure, it would be important to know how long an aggregation of fish is likely to remain in the refuge. This paper considers the question of how to design a survey for assessing the persistence of fish in an area of about 220 km^2. It also provides an analysis of survey data collected in such a region off the coast of Yorkshire during a two-week period in January this year (2000).

Two techniques for monitoring fish movement predominate: tagging (e.g. Metcalfe and Arnold, 1997) and acoustic monitoring (e.g. Foote *et al*., 1987; Simmonds *et al*., 1992; Misund, 1997). While tagging has many attractive properties, the timing of tag recovery cannot be controlled. As interest centres on persistence over periods of a few weeks, tagging studies are not practical. Acoustic surveys, though suited to short-term monitoring studies, also have a number of disadvantages. Firstly, it is difficult to know precisely which species are being observed acoustically. Secondly, it is usually impractical to follow individual fish schools, which implies fish movement must be inferred from changes in distribution, at some cost to the quality of inference. Despite these difficulties, we demonstrate in this paper that acoustic surveys provide insight into the persistence of fish aggregations.

Previous work on fish aggregations have largely been restricted to observations on the vertical distribution of schools, and their effect on acoustic biomass estimates and bottom trawl survey estimates (Clark and Green, 1990; Boudreau, 1992; Aglen, 1996; Jakobsen *et al*., 1997). There are also studies documenting the movements of individually tagged cod (e.g. Arnold *et al*., 1994). No previous studies on the spatial and temporal extent of young cod aggregations in the North Sea have been published to our knowledge. Studies describing the spatial interrelationship of fish shoals and plankton patches have, however, been published (e.g. Mackas *et al.*, 1997; Swartzman *et al.*, 1999).

MATERIAL AND METHODS

The primary motivation for considering short-term harvest refuges within ICES was to protect juvenile cod. This being the case, we decided to mimic conditions likely to lead to the creation of a juvenile cod refuge. We asked fishermen of the UK National Federation of Fishermen's Organizations (NFFO) to indicate an area where they were encountering high concentrations of juvenile cod. The fishing industry took a strong interest and sent an observer, Fred Normandale, to assist us. On his advice, we headed for an area off the coast of Yorkshire (54.4ºN, 0.3ºW), where we tried to find these young cod. On locating the fish, we would create a 220 km^2 survey region and monitor the distribution of fish in the area acoustically, whilst catching, tagging and returning as many fish as possible. The location of trawl samples (stations) was constrained by numerous shipwrecks in the vicinity.

We used 38 kHz and 120 kHz EK500 echo sounders to collect acoustic recordings, which we processed subsequently using Echoview software (SonarData, 1998). In all such acoustic analysis we focused attention on the region extending from 0.5 to 5 m above the seabed in an effort to obtain the highest possible representation of cod in the acoustic echoes. During daylight hours, we took trawl samples to assess the proportion of cod in the acoustic data. The representation of cod in the trawl data was the primary criterion in the final selection of the survey site.

The acoustic survey consisted of 19 separate survey grids (a grid is a sequence of transect lines), of which 15 were in the vicinity of the designated refuge site. These 15 grids are depicted in Figure 1, while the UK coast is shown with dark-grey regions. Grids 10-16 correspond to the location of the final refuge site. Overlaid on each grid is a contour plot of acoustic S_A values (in m^2/Nm^2) from the 120 kHz transducer. In these contours, darker contour colours signal the higher S_A values (S_A values are usually assumed to be proportional to biomass). These contour predictions were made by weighting observations by the inverse of their squared distance from a given prediction site. Naturally, predictions outside of the grid area should be regarded with strong scepticism. Captions beneath each grid indicate the time period over which it was surveyed. Figure 2 was generated using the same techniques on the data from the 38 kHz transducer.

The contour plots in Figures 1 and 2 were intended to convey a pseudo-synoptic impression of changes in biomass distribution over time. Visual inspection of these indicates where the biomass is found reliably, and where there are fluctuations. Unfortunately, the temporal resolution is often insufficient to follow the movement of aggregations.

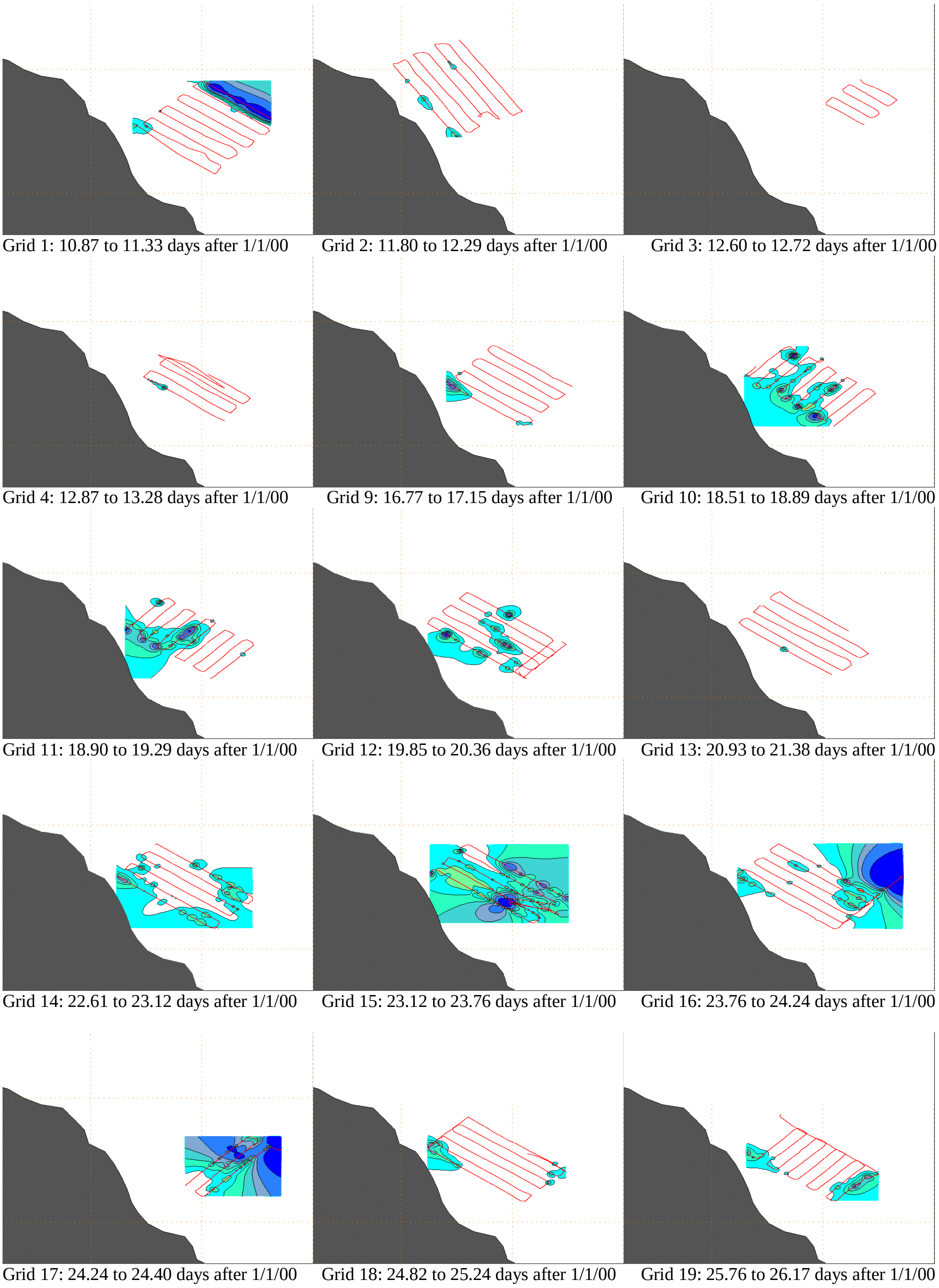

Figure 1. Grids comprising the survey. The coast of Yorkshire is indicated in dark grey at the bottom left-hand corner of each panel. Contour lines of S_A from the 120 kHz transducer are overlaid on these grids. The dark grey contours indicate the highest biomass, whilst the clear areas are lowest. S_A predictions outside of the grid area are shown for information. Under each grid, the time period over which it was surveyed is indicated. Grids 11 to 16 indicate the area that was finally designated as the harvest refuge.

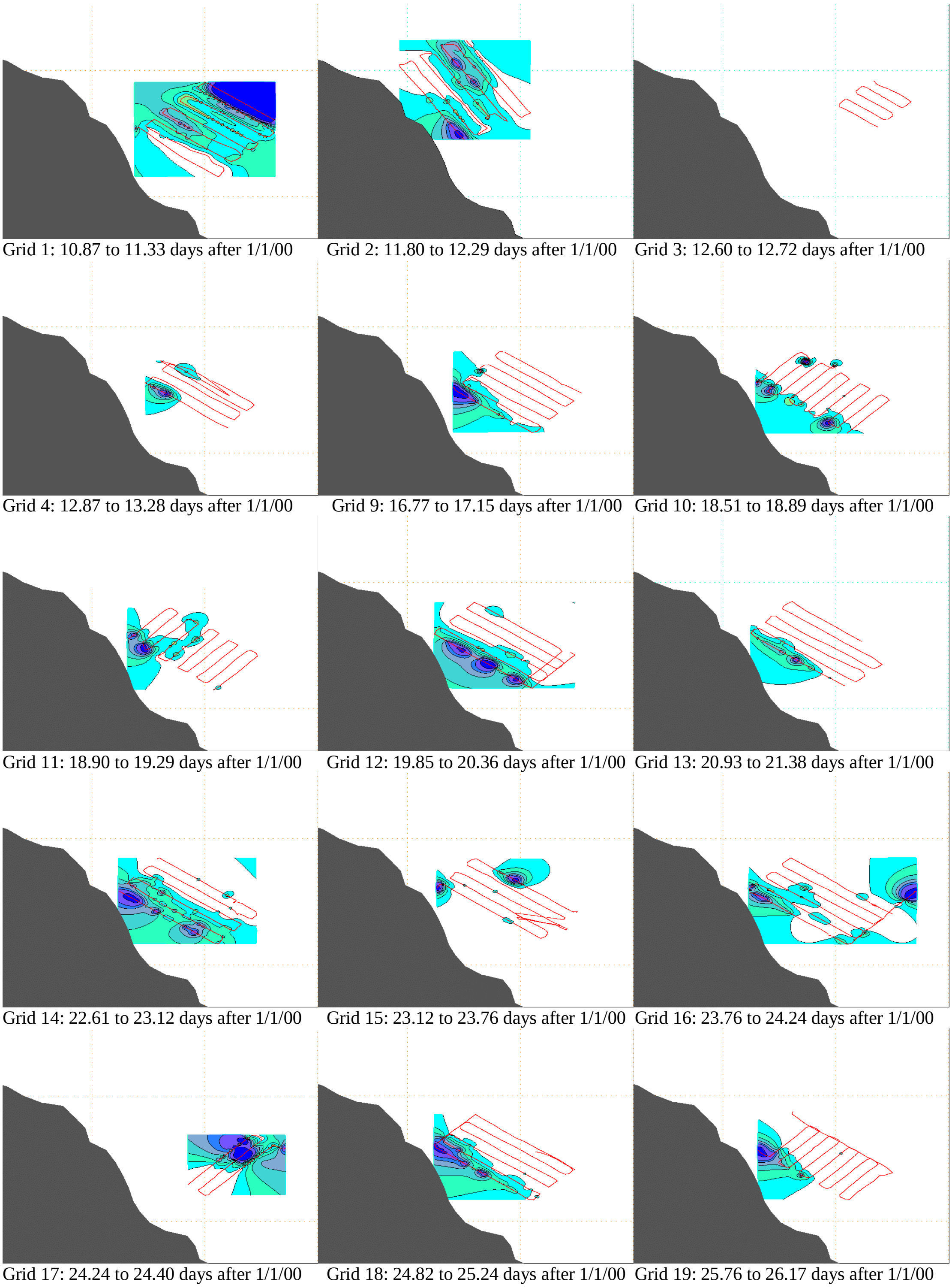

Figure 2. Grids comprising the survey. The coast of Yorkshire is indicated in dark grey at the bottom left-hand corner of each panel. Contour lines of S_A from the 38 kHz transducer are overlaid on these grids. The dark grey contours indicate the highest biomass, whilst the clear areas are lowest. S_A predictions outside of the grid area are shown for comparison. Under each grid, the time period over which it was surveyed is indicated. Grids 11 to 16 indicate the area that was finally designated as the harvest refuge.

An enlarged view of the designated refuge site is shown in Figure 3.

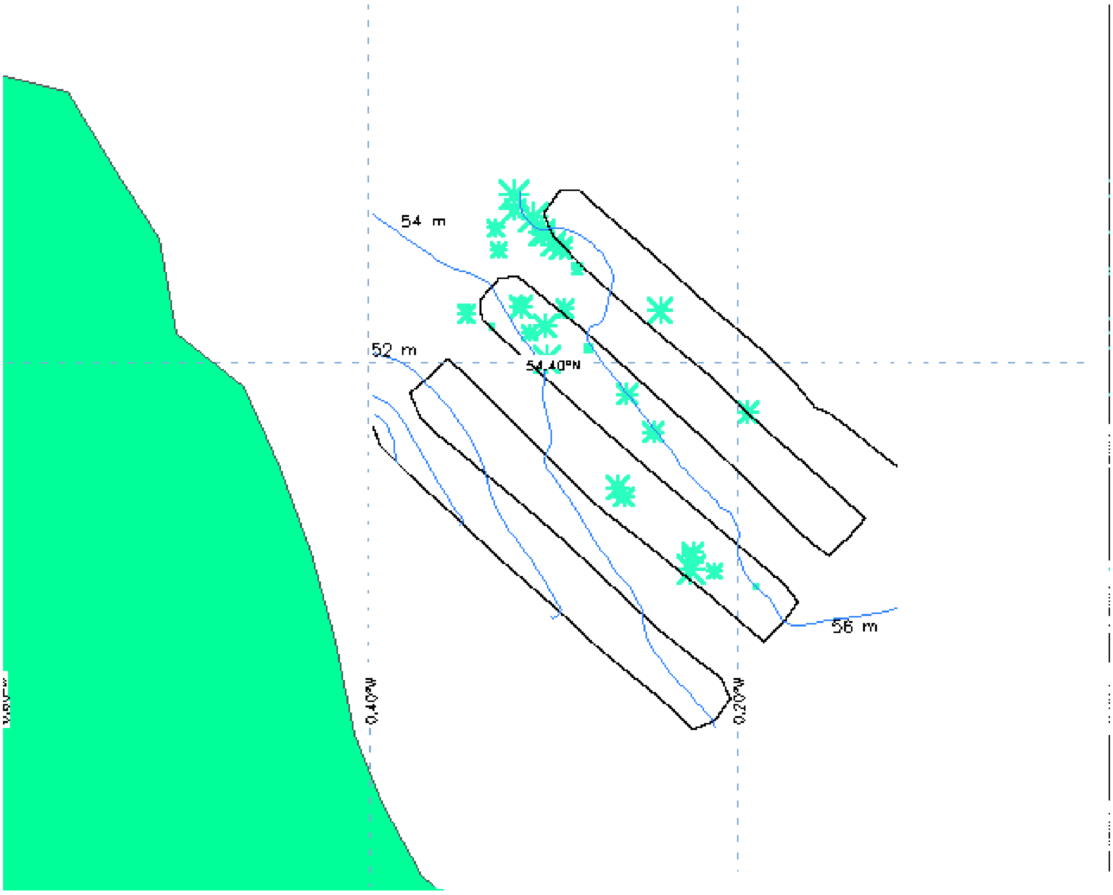

Figure 3. This figure indicates the survey region with the black solid transect line. The solid grey region indicates the UK coast, whilst the light grey curves are contours of bottom depth at 2m intervals. The locations of the trawl samples are indicated by the asterisks, whose size is proportional to $\log_e(1 + \text{cod catch in kg/h})$.

A good initial investigation into persistence of fish in the survey area involves averaging the S_A values (in m^2/Nm^2) over each grid. Examination of these average values should suggest trends in the total biomass in the region. However, in dealing only with the average S_A values observed over each grid one runs the risk of glossing over cyclic fluctuations due to diel migration or tidal forcing. Such cyclic patterns could induce a biased perception of temporal persistence because the grids were sampled at different times of day and in different directions (Figure 1). To try to identify any diel patterns, we fitted a generalized additive model, GAM (Hastie and Tibshirani, 1990). This approach has the advantage of using all of the acoustic data, rather than just the averages. In addition, a GAM model can present a clearer picture of how any temporal patterns change spatially (c.f. O'Brien and Fox, 2000; Fox *et al.*, 2000).

The GAM model we used was as follows:

$$\log_e(S_A) =$$

$$\mu + lo(d_a) + lo(d_o) + lo(d_a, d_o) + lo(t) + lo(t,d_o) + lo(t, d_a) + \gamma_1\sin(2\pi t) + \gamma_2\cos(2\pi t) + \varepsilon$$

where d_a represents the distance along shore in km, d_o the distance offshore (km), and t the time (in days) from the start of January. The *lo* term represents a LOESS (c.f. Chambers and Hastie, 1991) smoothing function to be determined by the GAM fitting algorithm. The sine and cosine terms were designed to represent cycles with a 24-hour period. The values of the parameters $\{\gamma_1, \gamma_2\}$ are to be estimated. Denote this model M2. The model fits with this model to the data from the 38 kHz and the 120 kHz transducers are to be compared to the null model:

$$\log_e(S_A) = \mu + \varepsilon$$

where μ represents an intercept term and ε denotes a random error term assumed to be Normally distributed with mean zero and constant variance. Denote this model M1. Implicitly, the models M1 and M2 assume that S_A has a log-normal distribution. Alternative distribution assumptions might be plausible such as a Gamma distribution with a log-link but these will not be considered further in this paper.

RESULTS

Though considerable differences between the two frequencies are evident in Figures 1 and 2, both suggest that fish are found most reliably on the inshore edge of the region, particularly on the western tip, an area difficult to fish because of numerous wrecks. Both frequencies suggest brief appearances of large fish concentrations in eastern offshore areas. Differences between the two frequencies are due to the resonance patterns of the targets, to the 12 m separation between the two transducers, to differences in the results of the bottom tracking algorithms, and (possibly) to the fact that neither transducer was calibrated. Visual inspection of the echograms suggested that concentrations of fish could be considered part of the bottom signal on one frequency, while being treated as fish on the other. Despite the lack of calibration, both transducers can provide relative indices of abundance, but absolute S_A values should not be compared with other studies or between frequencies.

Figure 3 shows the location of trawl samples in the survey area, with symbols whose size indicates the natural logarithm of cod catch weight per hour. The true catch rate was incremented by 1 kg/h prior to taking the logarithm so as to prevent negative values. Cod were a relatively small portion of the catch of all demersal fish, most of which were whiting. As, shown in Figure 4, fewer than 1% of the 921 cod captured were above 50 cm in length. Figure 5 indicates the catch rates for demersal fish other than cod using symbols sized as those in Figure 3. Figure 6 indicates that the proportion of cod in the catch slowly increased as the survey progressed, as much an indication of an increased ability to catch them as of their increasing abundance.

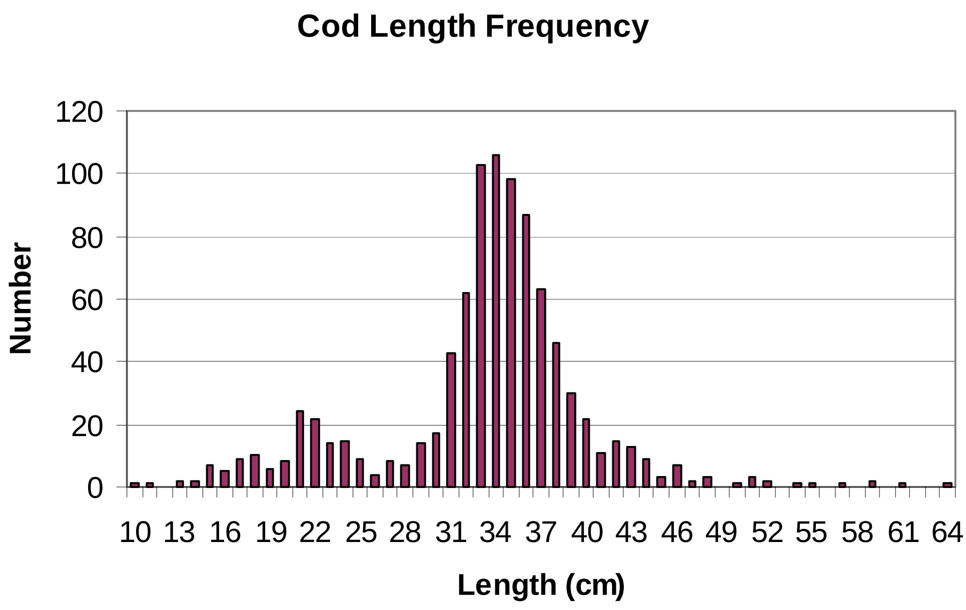

Figure 4. This figure indicates the length distribution of cod captured over the entire survey.

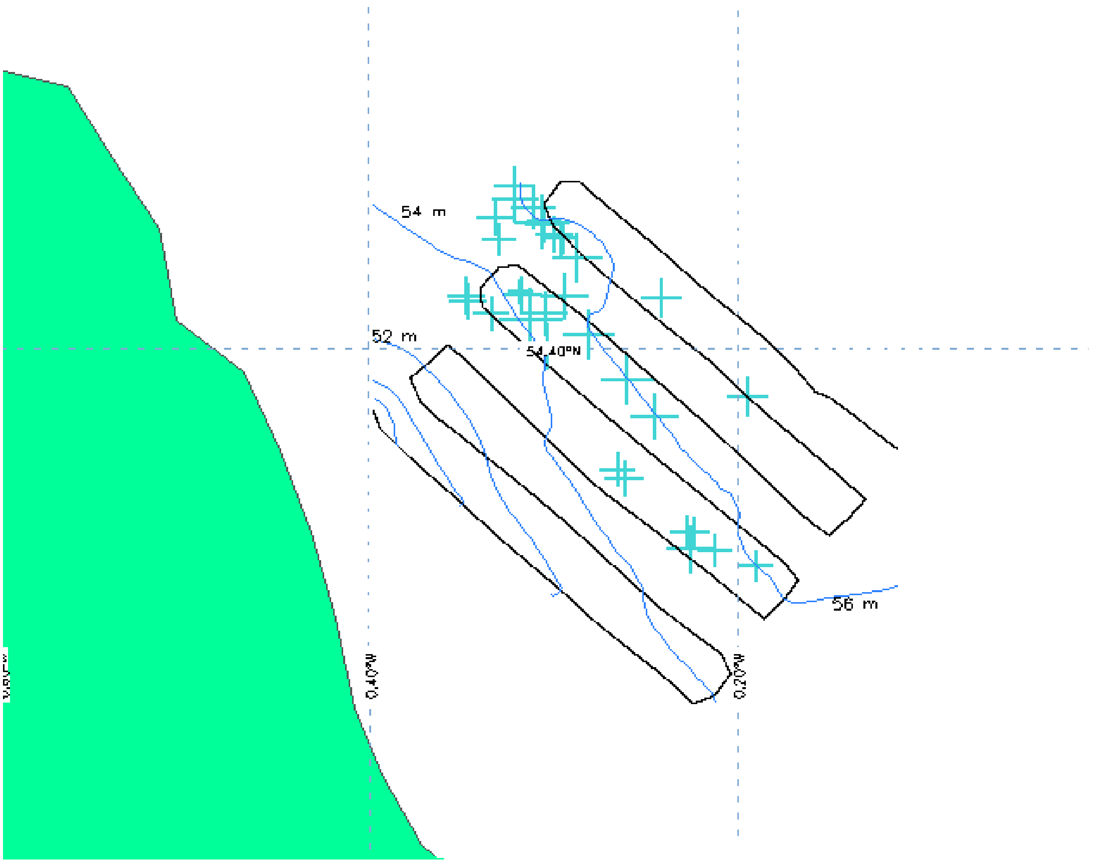

Figure 5. This figure indicates the survey region with the black solid transect lin The solid grey region indicates the UK coast, whilst the light grey curves are contours of bottom depth at 2m intervals. The locations of the trawl samples are indicated by the crosses, whose size is proportional to $\log_e(1$ + demersal fish catch other than cod in kg /h).

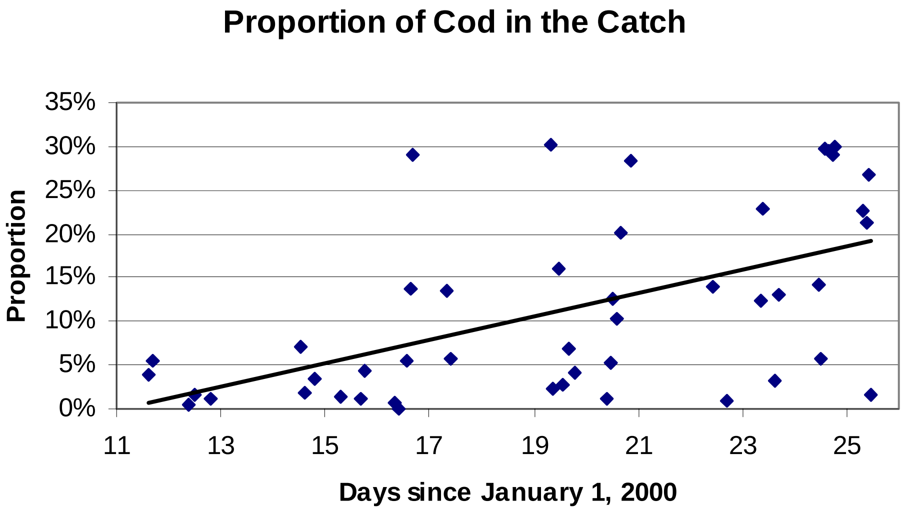

Figure 6. The increasing trend in the proportion of cod by weight in the total catch of demersal fish.

In Figure 7, the average 38 kHz S_A for each of the grids in Figure 2 is indicated with a circle, while whiskers indicate the 95% confidence intervals around these points. The curve smoothed through these points was obtained through a locally weighted regression technique, LOESS (c.f. Chambers and Hastie, 1991) whereby points were weighted by the inverse of the grid S_A variance. If representative, this curve suggests that the biomass of fish in the survey area can fluctuate by as much as 40% in the space of three days. It is important to remember that altering the smoothing parameter would change this perception but not the overall temporal pattern. A broadly similar pattern was obtained from the readings on the 120 kHz transducer (Figure 8), using the same smoothing parameters. Examination of the catch time series (Figure 9) suggests little resemblance to the acoustic signal, but trawl samples provide a much less effective indication of fish movement.

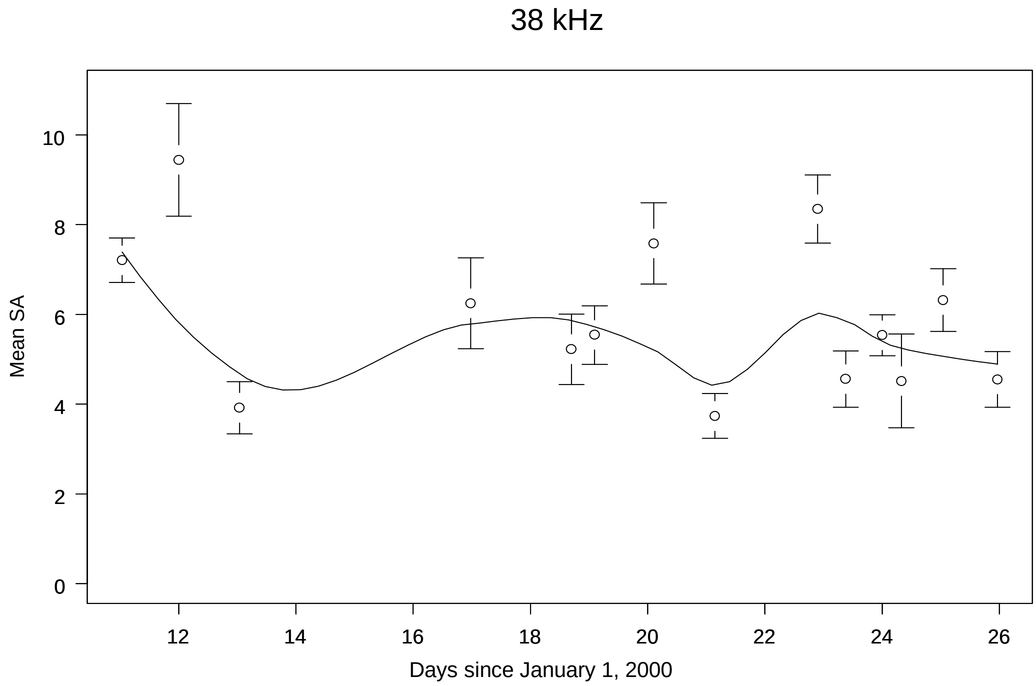

Figure 7. The average 38 kHz S_A for each of the grids surveyed in Figures 1 and 2 is indicated with a circle, whilst whiskers indicate the corresponding 95% confidence intervals. The smoothed curve was obtained through using LOESS as described in the text.

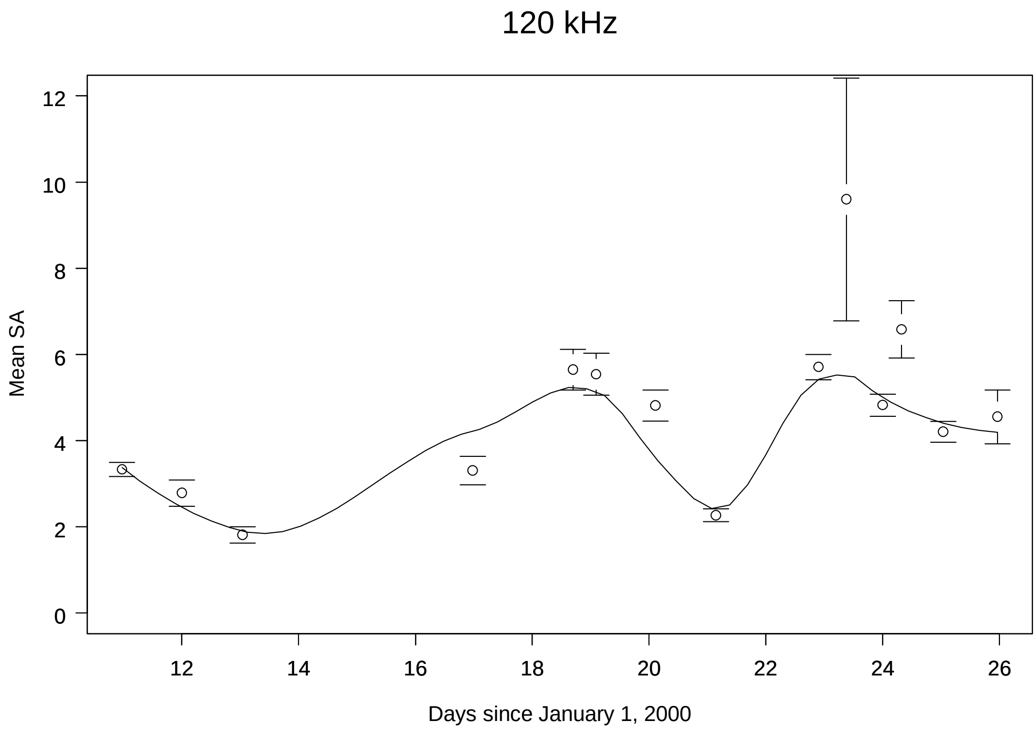

Figure 8. The average 120 kHz S_A for each of the grids surveyed in Figures 1 and 2 is indicated with a circle, whilst whiskers indicate the corresponding 95% confidence intervals. The smoothed curve was obtained through LOESS.

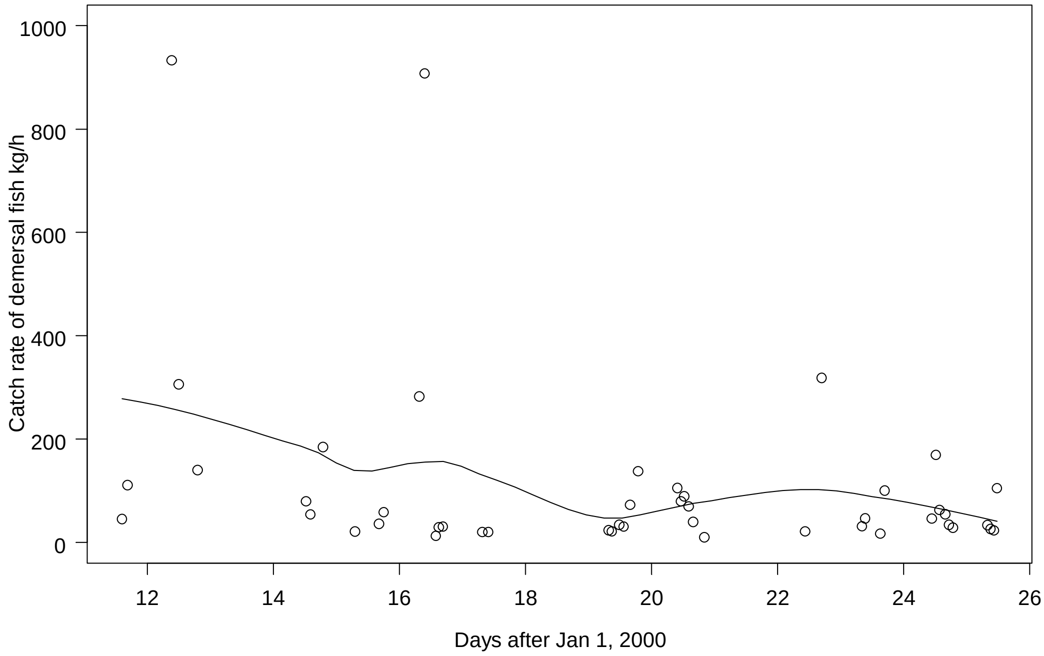

Figure 9. Catch rates (kg/h) for all demersal fish over the course of the survey (depicted by circles). A line was smoothed through these points using LOESS.

All terms of the GAM model M2 were significant (Table 1).

Frequency	M2 deviance/ M1 deviance	Distance along shore	Distance offshore	Time	Offshore, Along shore	Offshore, Time	Along shore, Time
120 kHz	773/1229	2.93 / 0.04	13.57 / 0	70.93 / 0	19.26 / 0	10.68 / 0	22.23 / 0
38 kHz	1155/1975	6.13 / 0.001	13.12 / 0	25.64 / 0	26.16 / 0	23.58 / 0	14.27 / 0

Table 1. GAM fit diagnostics. The second column shows the deviance for the log-normal GAM model compared to that for the null model (change in degrees of freedom, 30.5). The significance of individual terms is given in the other columns (F-statistic/p-value).

Modelling diel cycles using linear combinations of $\cos(2\pi t)$ and $\sin(2\pi t)$ (as in the M2 model above) yielded a significant improvement in model fit over a model without such terms (ANOVA F-test, $p = 0$). Figures 10 to 15 show components of the GAM fit to 38 kHz data. We draw particular attention to Figure 12, the temporal component, which is the prime objective of the analysis with GAMs and indicates the overall trends in biomass in the refuge area. The pattern is not dissimilar to that in Figure 7, but the implied fluctuations in fish abundance are more pronounced; for example, the change in the effect on the logarithm of density from –0.2 to 0.2 indicates fluctuations of ~50% in a period of two to three days.

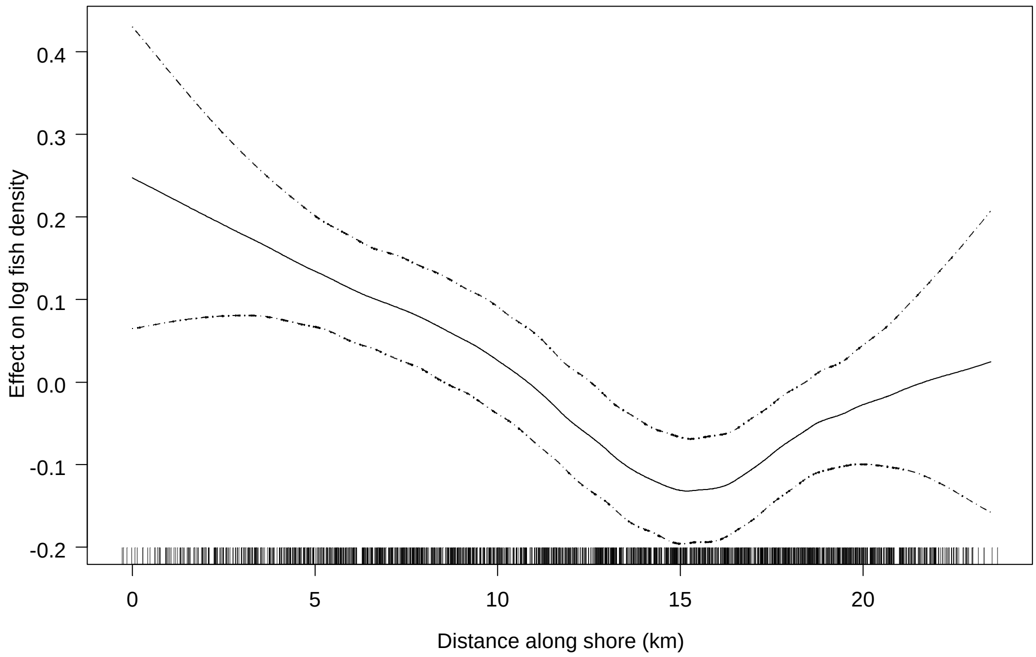

Figure 10. The effect of distance along shore d_a on the expected $\log_e(S_A)$ value; namely, local fish density, for the 38 kHz transducer. The rug (tick marks) along the bottom of the graph shows the location of the data points. The 95% confidence limits are shown with broken lines.

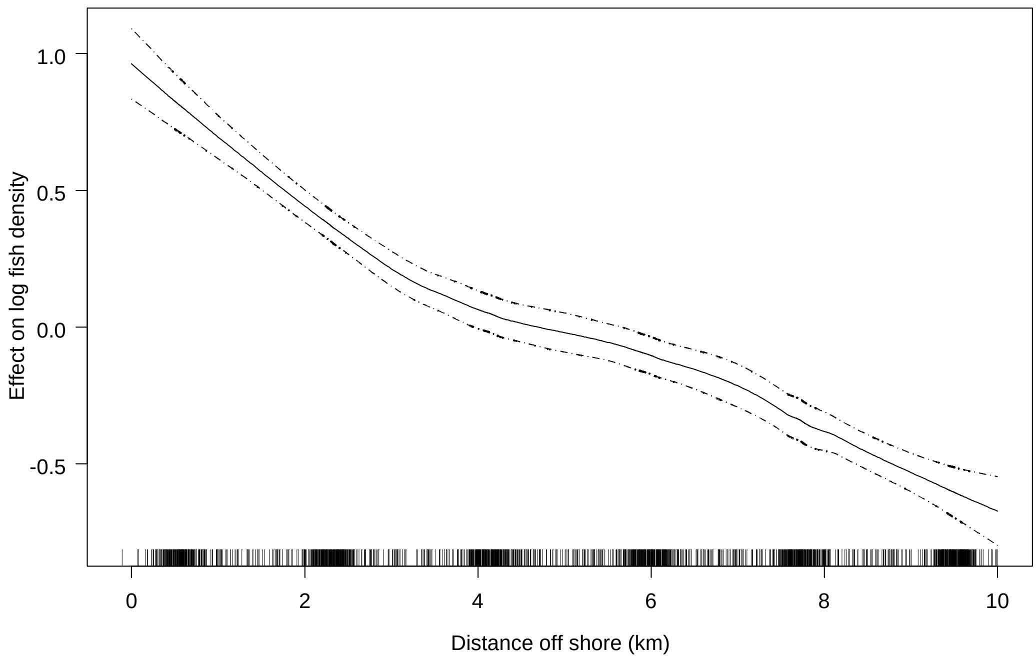

Figure 11. The effect of distance offshore d_o on the expected $\log_e(S_A)$ value; namely, local fish density, for the 38 kHz transducer indicating that there were more fish inshore.

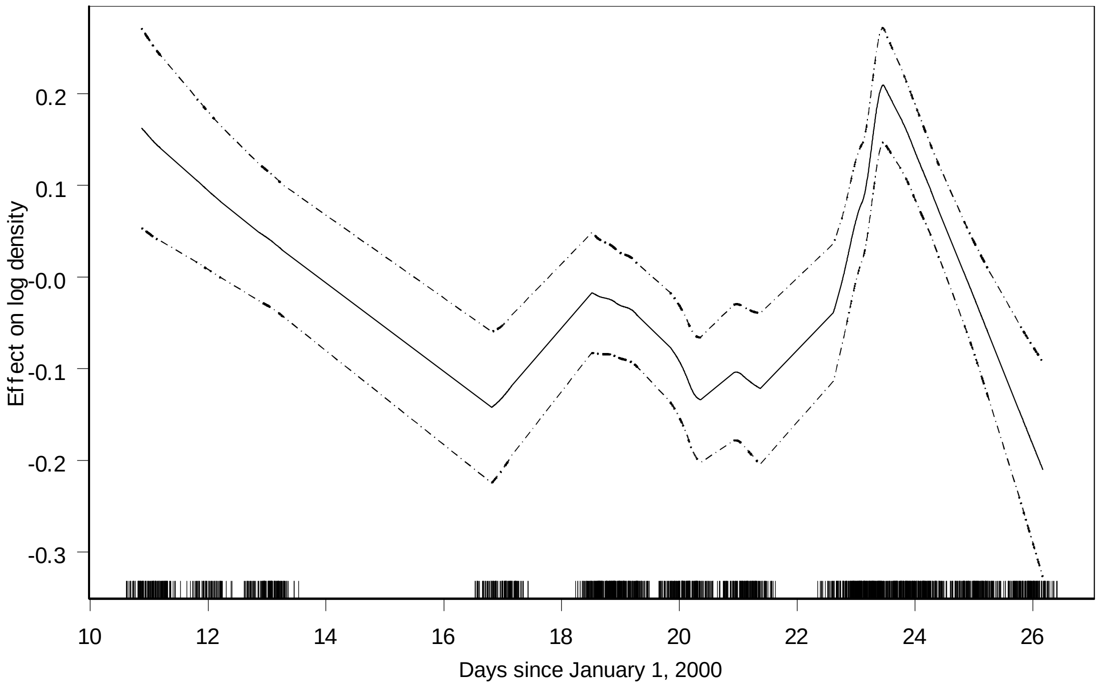

Figure 12. The effect of time on fish abundance as detected by the 38 kHz transducer.

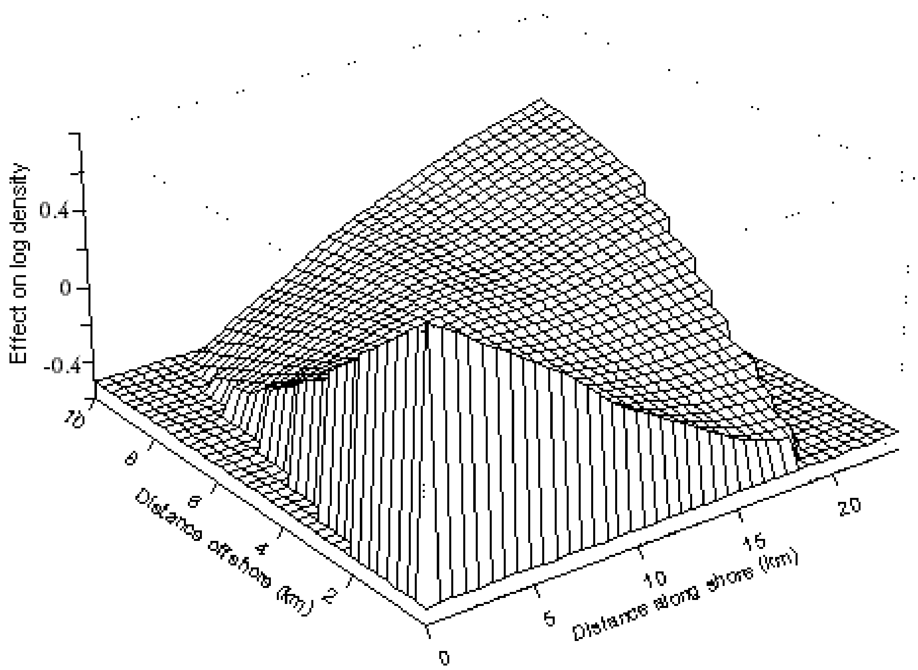

Figure 13. The effect of the interaction between distance offshore and distance along shore as detected by the 38 kHz transducer indicating that most of the fish were on two diagonally opposite corners of the grid.

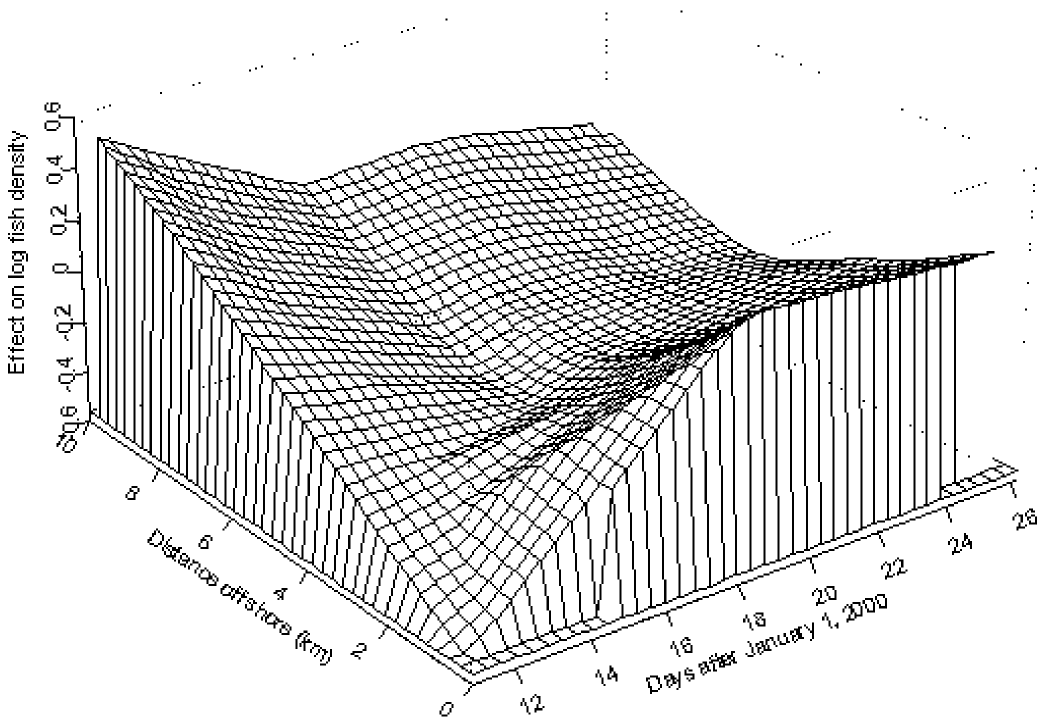

Figure 14. The decline in abundance of offshore fish over time, whilst the abundance of inshore fish increased according to the data from the 38 kHz transducer.

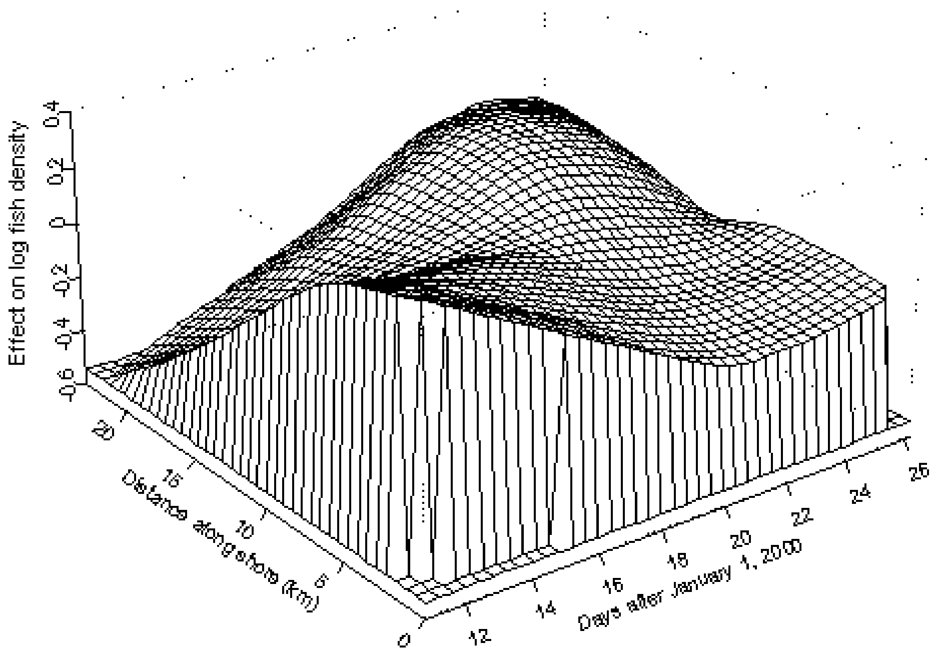

Figure 15. The influx of fish on the easterly end of the survey region and the outflow on the western end, according to the data from the 38 kHz transducer.

In Figures 16-21 we show the same plots for a GAM model fit to the 120 kHz transducer acoustic data. Figure 17 clearly indicates that there were more fish inshore. Differences in the temporal signal from that evident on the 38 kHz transducer data are evident in Figures 18 and 21. In the case of Figure 18, the high peak near January 24th is due to a single highly dense fish aggregation that was indistinguishable from the bottom with the 38 kHz transducer. The GAM model suggests an inshore pattern almost exactly opposite of the offshore pattern (Figure 21). Such a pattern could be a result of fish moving inshore from January 11th to 19th and then moving offshore from the 20th of January. Other explanations are certainly possible.

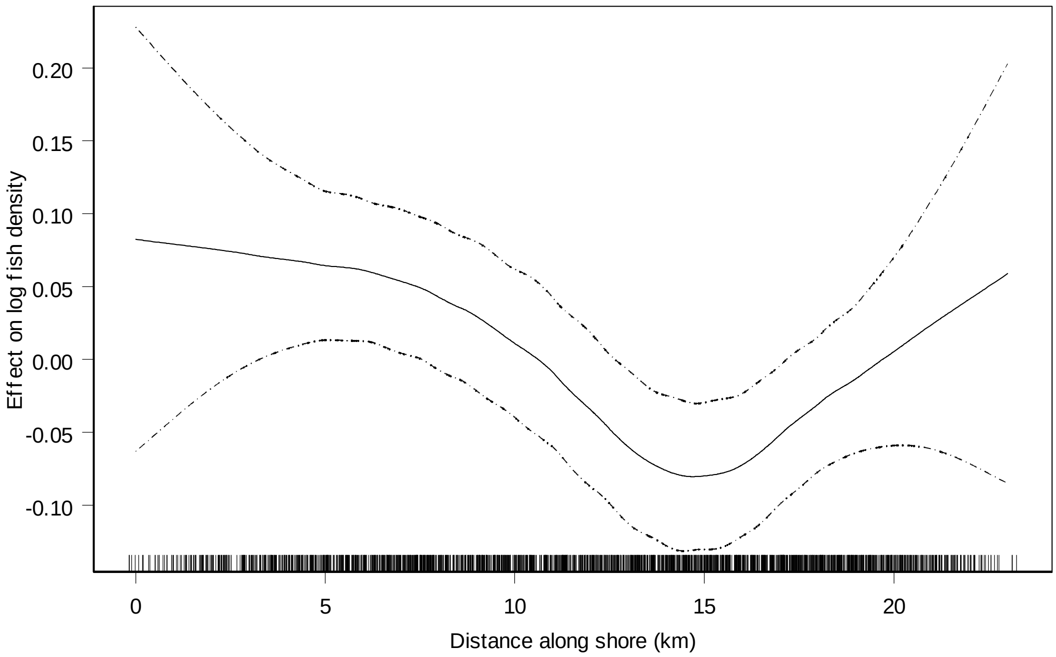

Figure 16. The effect of distance along shore on the expected $\log_e(S_A)$ value for the 120 kHz transducer.

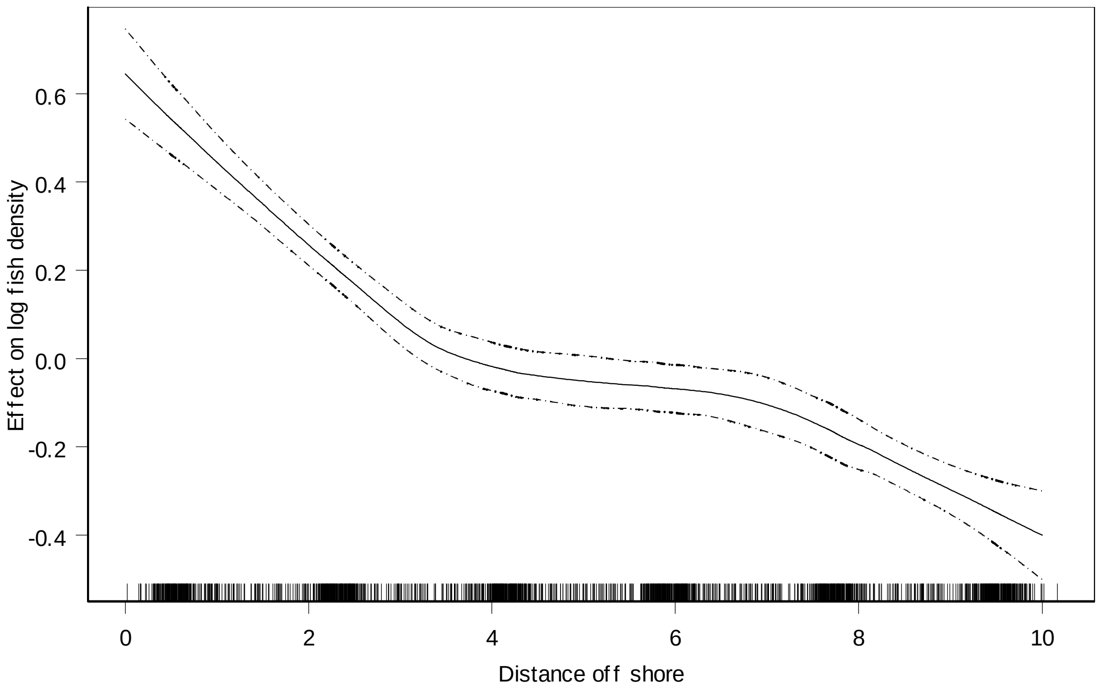

Figure 17. The effect of distance offshore on the expected $\log_e(S_A)$ value for the 120 kHz transducer.

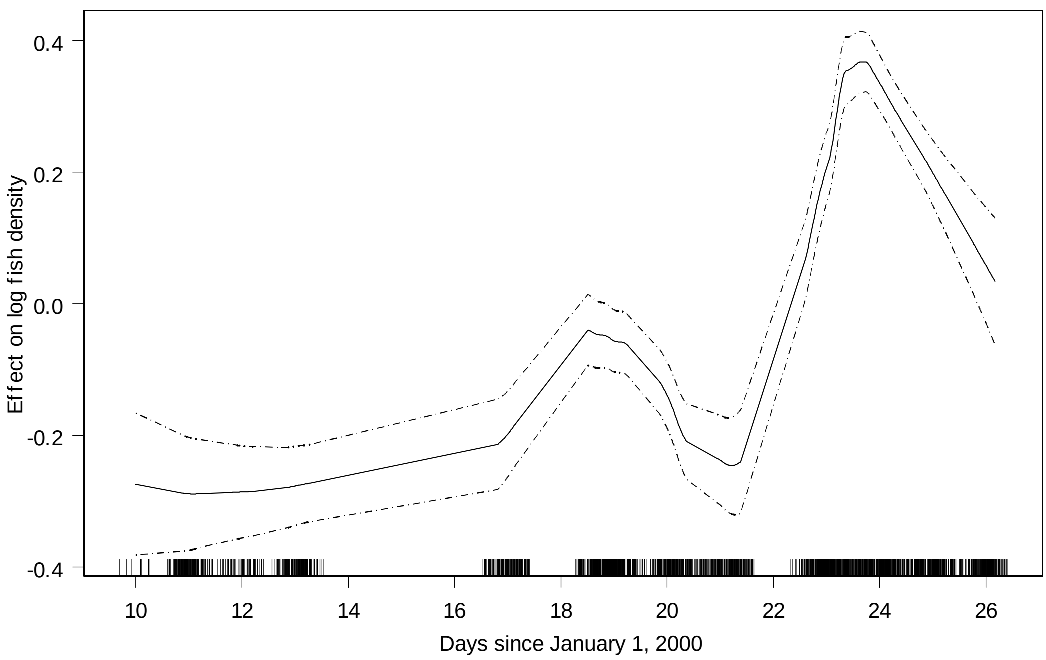

Figure 18. Temporal pattern detected on the 120 kHz transducer.

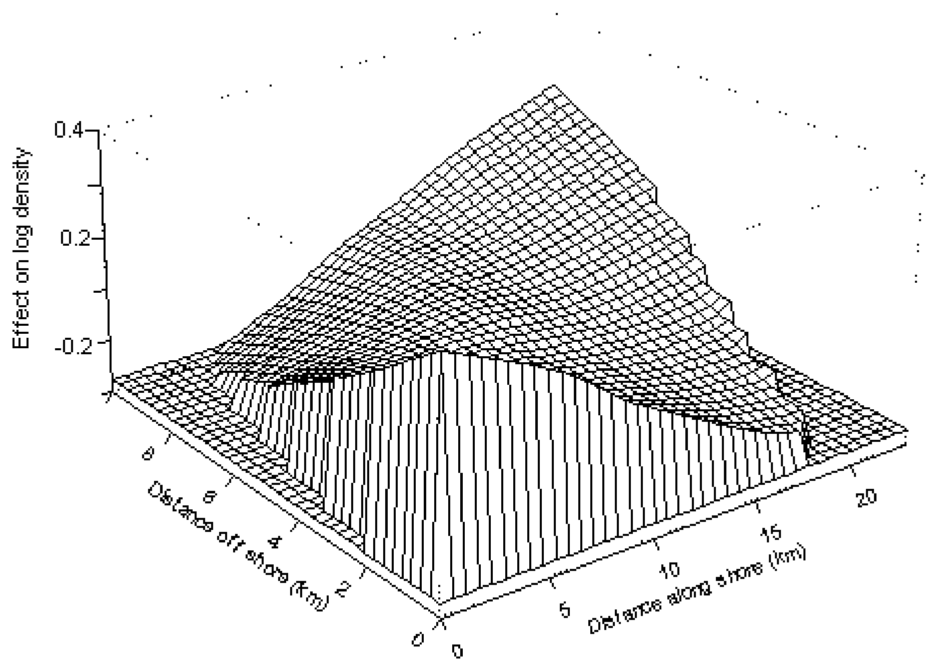

Figure 19. The effect of the interaction between distance offshore and distance along shore as detected by the 120 kHz transducer indicating that most of the fish were on two diagonally opposite corners of the grid.

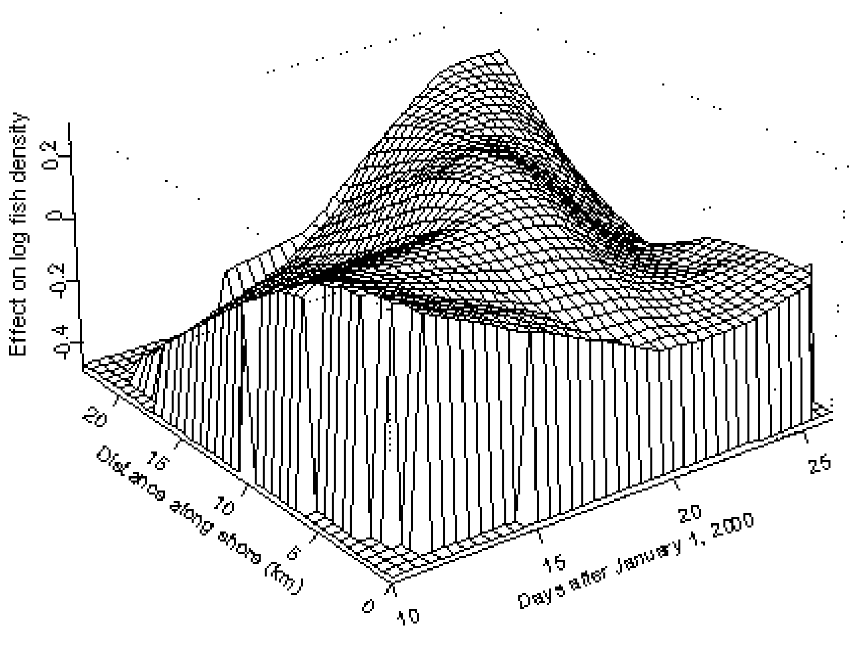

Figure 20. The influx of fish from the easterly end of the survey region and the outflow from the western end, according to the data from the 120 kHz transducer.

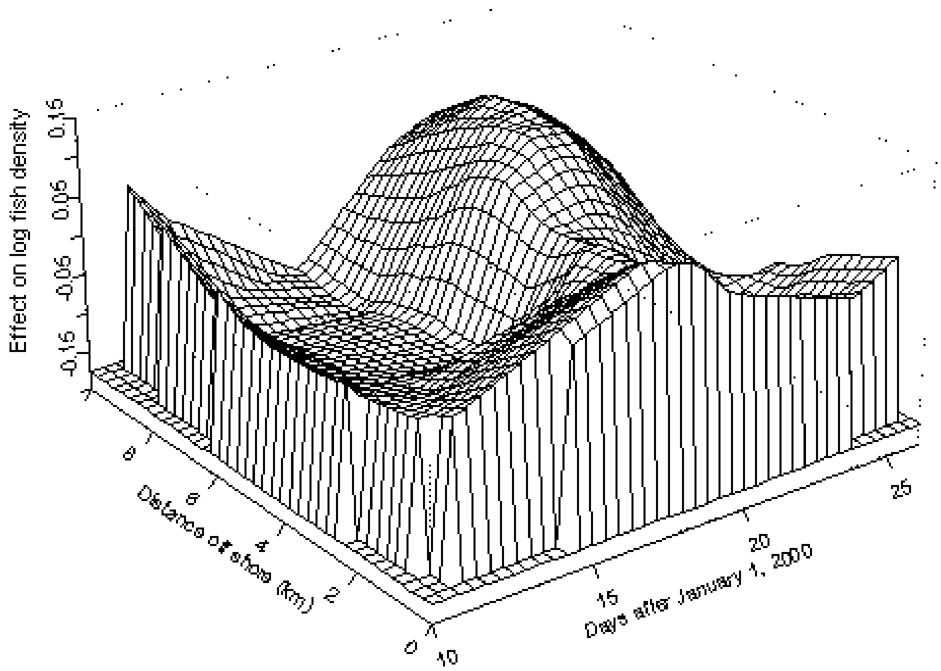

Figure 21. The change in abundance of offshore fish over time, according to the data from the 120 kHz transducer.

DISCUSSION

Our investigation into the persistence of juvenile cod in a 220 km^2 area suggested that the biomass in a region this size would fluctuate by about 40-50% in the space of about three days. In view of this level of fluctuation, significantly larger regions would be required to provide adequate protection to juvenile cod. Investigation of persistence in larger areas by similar acoustic methods might benefit from the use of several vessels, to provide more rapid grid coverage and thus better resolution in the temporal signal.

Our acoustic investigation suffered from an inability to discriminate between cod and other demersal fish. Any conclusions we reach about cod must rely on an assumption that cod movements are similar to those of the entire demersal assemblage.

We found that GAMs provided a useful tool for extracting diel and tidal effects, which might affect the temporal signal in a small area. The GAMs also provided insight into the interactions between movement and grid position. Nonetheless, although GAMs and smoothed grid averages provide useful quantitative summaries of the acoustic data, we found a visual pseudo-synoptic presentation of the acoustic data provided the most insight into fish movement in the area.

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