A MAXENT TOMOGRAPHY METHOD FOR ESTIMATING FISH DENSITIES IN A COMMERCIAL FISHERY

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Abstract. A Maxent tomography method is used to estimate densities of fish in the Hoki fishery off the West coast of New Zealand using data from commercial trawling. The individual trawls are the tomography lines with information on the start and end positions of the tow and the weight of fish caught. The Maximum Entropy algorithm is used to find the best estimate of the fish density distribution. Contour and density plots of relative fish density have been obtained for sequences of weekly data in several fishing seasons.

Key words: Tomography, Fish, New Zealand, Maximum Entropy

1. Introduction

Hoki, *Macruronus novaezelandiae*, is a fish species widely distributed in New Zealand waters. The largest stock is thought to have feeding grounds in the Sub-Antarctic region south of New Zealand but their spawning occurs each July and August off the West Coast of the South Island (See Figure 1). The fishery on the spawning grounds is the largest commercial fishery in New Zealand. About 60 trawlers, each up to 100 metres long, tow nets up to 100 metres square for up to 50 km at one time. One catch can contain 100 tonnes of hoki.

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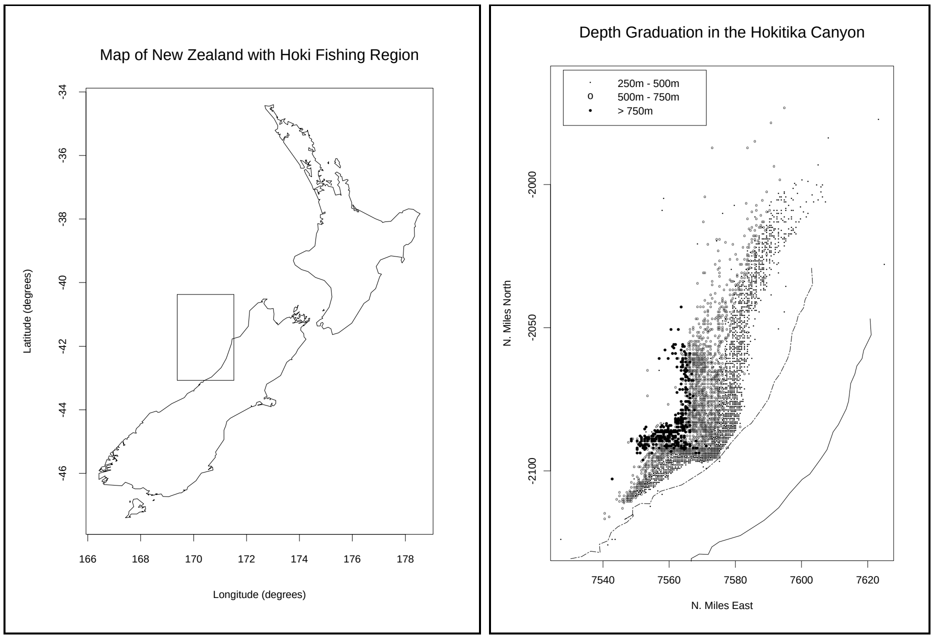

Figure 1. The location of the New Zealand hoki spawning fishery is shown in the left figure. The right figure shows the start positions of tows for 1993, the coast, and the the 25 n. mile fishing limit. The depth indication shows the deep underwater Hokitika Canyon where the hoki congregate at the start of the season

The fishery is controlled by the New Zealand Government which is required to set sustainable quotas. Large vessels are restricted from fishing within 25 nautical miles (n. miles) from the coast.

The Government monitors the hoki resource by a variety of fisher-independent and fisher-dependent methods. Information obtained by these methods is combined with population models to provide estimates of biomass. Fisher-independent methods include acoustic surveys on the spawning grounds and random trawl surveys on the feeding grounds. These observations are too sparse to give accurate spatial information about the fishery.

Fisher-dependent data from the commercial trawling activities are used for Catch Per Unit Effort (CPUE) calculations [2]. Here catch per nautical mile is assumed to be related to fish density. The true relationship depends on the spatial dynamics of the fishery, but these are poorly understood. Better information about local density fluctuations would be useful for managing the fishery and predicting the effect of new management measures. Attempts have been made by Vignaux [1] to determine more detailed structure using CPUE data.

Maximum Entropy (MaxEnt) imaging methods appear to be a promising technique for using the trawl data to get this more detailed information about spatial and temporal density variations. The individual trawls (called tows) form segments of tomographic scans from which densities might be estimated. Maxent methods such as those by Gull and Daniell [3] have been used to develop images from tomographic data in astronomy. Here they are applied to a more down to earth situation.

2. Data and Method

The data for our analysis comes from standard forms filled in for each tow undertaken by the commercial trawling fleet during the last six seasons. Each report, made aboard the vessel, includes the date and time of the tow, the start and end positions, and the size of catch. The size, net and other characteristics of the vessel are also known.

Tows tend to be irregularly spaced and are neither orthogonal nor randomly distributed. The reason for this is that fishers aim to trawl high concentrations of fish, thus the majority of the fleet will be found fishing in the areas which have recently had high catches. The data source is therefore not well designed for estimating fish densities.

The data collected may not be reliable as recording is done under uncontrolled conditions. Error checking is particulary difficult as it is done some time after the observation. Obvious errors are removed, but it is probable that many remain. It is therefore important to check that results obtained are not too sensitive to their effects.

The weight of fish caught in a tow not only depends on the density of fish but also on the size of the net, characteristics of the ship towing it, and other factors. A linear multiplicative model was fitted to standardise the catches so that data from tows would be more comparable:

$$\frac{C_i}{l_i} = k_1 k_2 k_3 \ldots \exp(\epsilon_i).$$

Here C_i is the observed catch in tow i, l_i is the length of that tow, k_1, k_2, k_3, etc. are fitted regression terms reflecting the effect of other factors on the catch. ϵ_i is the residual from the fitted model and represents fluctuations in catch rate that cannot be explained by other factors. Some of this residual may be explained by spatial variation in fish density on a local scale. The expression is made additive by a logarithmic transformation.

The model was fitted using stepwise regression. The variables included were time within the season, vessel nationality (a surrogate for many behavioural factors), time of day, year, vessel length, latitude and headline height. The most significant variable is a seasonal effect, modelled as a cubic continuous variable. The second most important variable is nationality, then come the time of the day and the year effect (a surrogate for changes in total biomass from year to year). Vessel size, net size and tow latitude are minor variables. These variables explain only about a quarter of the total variance. Apart from any variation due to spatial fluctuations in fish density there will also be a great deal of noise.

A standardised catch is defined as:

$$C'_i = \frac{C_i}{k_1 k_2 k_3 \ldots} = l_i \exp(\epsilon_i) = \int_l \rho(l) dl,$$

where $\rho(l)$ is the relative linear density at a point in the tow. This model is approximated by dividing the area into a number of squares, j, setting ρ_j (the image) as the mean density in square j and l_{ij} (the transition matrix) as the distance traversed by tow i across square j. It is assumed that the tows are linear from start to finish. The model becomes

$$C'_i = \sum_j l_{ij} \rho_j$$

and provides the image to data tranformation.

V. A. Macauley's [4] programs, based on the algorithm by Skilling and Bryan [5], were modified for use in this study. These programs are written in C and were originally used for MaxEnt spectral analysis. The method was tested out on dummy data and it proved successful in reproducing images even with high noise levels in the simulated tow data.

In an earlier study Vignaux [1] found evidence for spatial correlations of fish density up to 11 n. miles and temporal effects lasting up to 14 days. Three different block sizes (4×4, 8×8 and 12×12 n. miles) were therefore tested in this study. Similarly data was aggregated into periods of 3, 7, and 14 days.

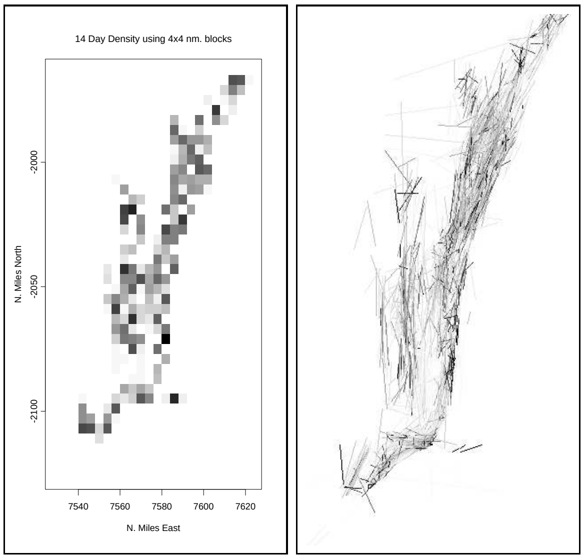

Figure 2. MaxEnt estimated densities for 4×4 squares and a 14-day period compared with catch rate. The darker the line for a tow, the more fish per n. mile.

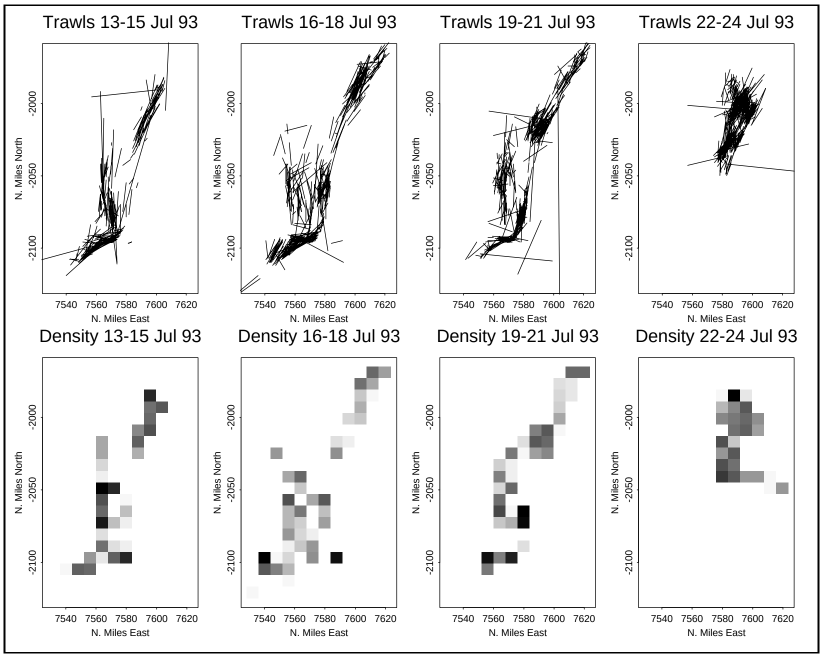

Figure 3. Four sequential 3-day periods in the 1993 season. The upper diagram show the tows, the lower the corresponding MaxEnt density estimates in 8×8 squares.

3. Results

The left side of Figure 2 shows that the MaxEnt method was successful in producing images of fish density at these scales. The data set used for that figure covers a period of 14 days and uses 4×4 n. mile squares. The error parameter had to be set quite high for the method to converge with this noisy data.

To compare the estimated densities in relation to the raw data, a catch intensity was calculated for each tow as the standardised weight of fish caught per n. mile. This is plotted on the right side of Figure 2 with darker lines indicating the stronger intensities. Comparing this plot with the MaxEnt plot on the left it appears that the MaxEnt results are consistent with the catch intensities on the tows. In this image there appear to be two major regions that had a lower catch rates, the first in the lower centre region of the plot and the other in the upper right region of the plot. Both methods highlight these features well.

Figure 3 shows the tows and corresponding density plots for a set of sequential 3-day periods from the peak of the 1993 season. 240 8×8 n. mile squares are used to cover the 15 thousand square n. mile fishing zone.

The density plots provide information about the fishery that cannot be determined by the tow information alone. Fishers in the northern region on 13-15 July had good catch rates and were followed by others so that from 16-21 July there were many tows in the northern fishing area, though densities do not seem to have been particularly high. By the end of the period all the fishers were concentrated in the northern region and we have no information about the density in the southern region.

Clearly not all of the anomalous tows have been removed from the data. For example the North-South tow in the third period which is over 120 n. mile long is likely to be the result of a recording or transcription error in the finish position. It is therefore necessary to be careful in interpreting the density when the data comes from only a few tows. The method was tested for sensitivity to the presence of such outliers. When an anomolous tow is removed from the data the image contrast generally increases without any change in the overall image.

3.1. DIFFERENT SIZE BLOCKS

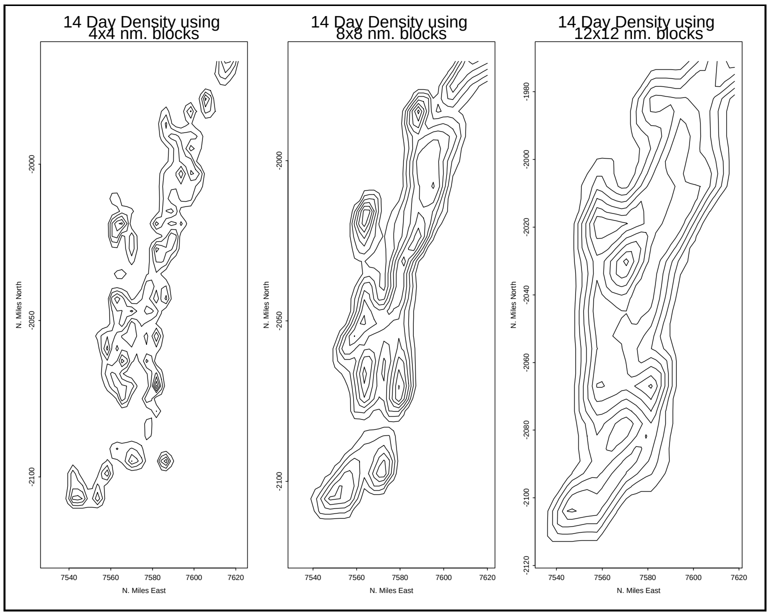

Figure 4. Comparison of contours produced by 4×4, 8×8 and 12×12 n. mile blocks

The data can also be presented in contour form as shown in Figure 4 for the same 14-day period using 4, 8 and 12 n. mile square blocks.

When the 4×4 blocks are used, the target sea area is divided into 960 squares. The image produced is reasonably fine but very variable in density making it difficult to pick up any overall patterns. The 8×8 blocks make it easier to spot these patterns, while still retaining the basic shapes and features of the data. Each of the 12×12 blocks represent the same sea area as nine 4×4 block and produce a very coarse image which lacks many of the interesting features of the data. The 8×8 n. mile blocks were selected for further analyses.

3.2. THE 1991 SEASON

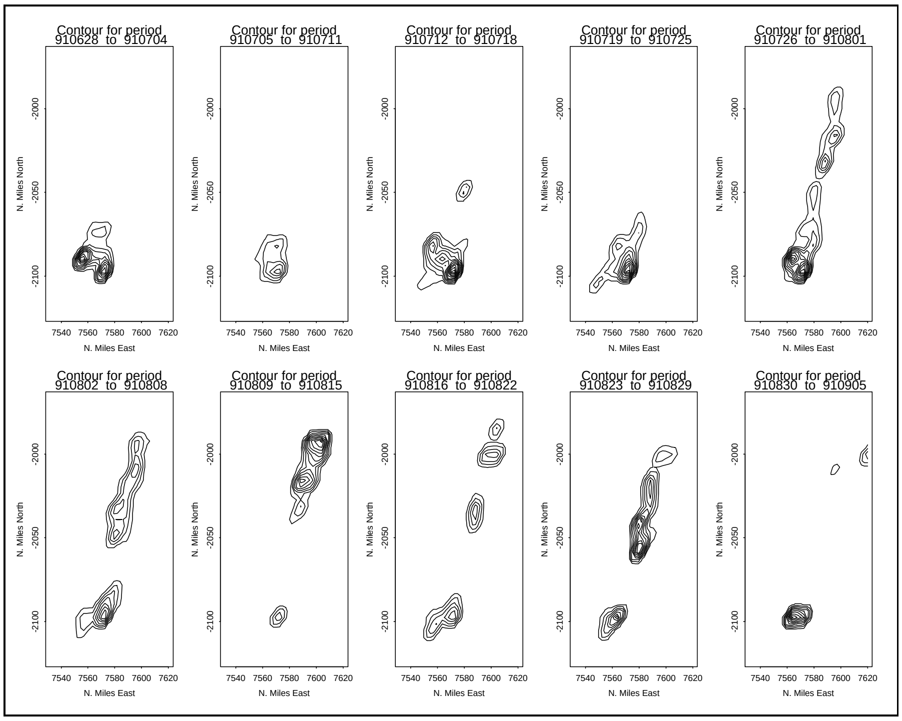

Figure 5. Contour plots of sequential 7-day periods for the 1991 season using 8×8 n. mile blocks.

To illustrate the type of analysis for which the MaxEnt densities will be used data from the 1991 season was examined. The results can be seen in Figure 5. Traditionally, fishers start the season trawling in the deep waters of the southern part of the fishery. As the season progresses they move in a northerly direction to shallower water. In 1991, fishing started in the south and continued there until the last week of July when the shift to the north began. From the beginning of August, the majority of tows were in the northern fishing region.

Figure 5 suggests a high density conglomeration of fish in the south at the start of the season which grows, spreads north and then splits into two. The southern concentration of fish remains throughout the season, but seems to contract.

4. Conclusions

Despite the noisiness of the data and the problem of tows which have not been specially arranged to provide the best patterns, the method appears to provide images of fish density which correspond to real phenomena.

It is difficult for conventional methods to obtain high resolution spatial pictures of the fishery due to the extreme length of tows which may reach 50 n. miles. The MaxEnt method manages to tease out density information on a smaller scale than the measurement tool.

The CPUE method is currently used throughout the world to estimate the biomass of fisheries. It is based on an untested assumption about the relationship between catch rates and biomass. Detailed information of the type produced in this paper is required to understand the relationship between the fishers and the fish and beween fishery management and sustainable yield.

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