Taihoro Nukurangi

Relating hill spawning aggregations to dispersed orange roughy on the Northwest Chatham Rise, June–July 2002

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7. EXECUTIVE SUMMARY

Tangaroa and *Ocean Ranger* were used to map the out-migration of spawning fish from Graveyard onto the flat area surrounding the hill. The study covered from mid-spawning to beyond the end of spawning (21 June–23 July). Biomass on the hills was monitored over the whole period acoustically and movements of fish on the flat after spawning were monitored by a trawl survey. The latter was based on a grid of one nautical mile squares and there were eight repetitions or snapshots.

A statistically significant migration of roughy from Graveyard, Scroll, and Zombie was found and migrating biomass was estimated to be 3775 t (c.v. 25%). About 40% of the overall biomass remained on the three hills. The outflow from the hills was between 4–9 July with the general best estimate of the peak 8-9 July. These estimates were based on fitting a logistic model to the acoustic biomass estimates of the Graveyard population.

Migrating fish were found on the flat to the west of Graveyard, initially in a 'marshalling' area immediately to the west of Graveyard and the other hills. They then moved west in a corridor between 1000 and 1100 m depth. The density of the migrating fish was five times that of the resident background fish in the denser parts, but well below that found in the migrations from the Spawning Box. The migrating fish were tracked out to 40 km from Graveyard. Two 'pulses' of fish were seen in the migration moving at about 10 km/day.

The grid survey trawls were used to investigate the relative catchabilities of the two vessels and there were no statistically significant differences between them. However, the power of the test was low and an actual difference of up to a factor of two is possible. Both vessels used

the same type of fishing gear, rigging, and procedures although they had different engine power.

By comparing the quantities of migrating fish in the grid trawl survey with what was on the hills during spawning an upper limit was estimated for Q ($1/q$ where q is the catchability). which was 10 with 95% confidence limits of 5–20. This result suggests that either trawl catchability on the flat is low or that most of the migrating fish had left the area before the grid survey had started. Q was also estimated by comparing the flat acoustic biomass estimates from the overall survey with relative trawl estimates made from the associated trawls. From these Q was 23.

8. OBJECTIVES

This report fulfils the reporting requirement for Objective 2 of Project ORH2001/01:

To determine relationships between orange roughy in spawning aggregations, and those dispersed at lower densities in the surrounding area. This involves investigating elements of:

- Variation in temporal and spatial distribution
- Spawning dynamics
- Aggregation dynamics
- Physical characteristics (bathymetry, hydrology)

9 INTRODUCTION

Orange roughy form dense aggregations in localised areas during the spawning season, typically on undersea hills. Surrounding these aggregations are dispersed fish at much lower densities extending over a wide region of generally flat sea floor ('the flat'). These 'background' roughy (which include fish in spawning condition) can account for a substantial proportion of the estimated biomass, because of the large area they cover relative to the tightly constrained aggregations. Lack of knowledge about how fish interact between the aggregations and the background, whether they spawn in scattered pockets or join the aggregations at some stage, and how stable the aggregations are over time, all create uncertainties in estimating biomass, and subsequent stock assessments. The Deepwater Fishery Assessment Working Group has discussed this situation at some length and Objective 2 of this project was conceived as a broad-brush approach to try to get new information to shed some light on these issues. As it happened, the data were restricted by the circumstances of the surveys and the priority given to obtaining a biomass estimate. Consequently, the work followed on the more limited aim of tracking the movement of fish away from the hills at the end of spawning and using this to estimate trawl catchability.

Currently, it is assumed that spawning roughy move into the wider Northwest Hills area, aggregate on and around the hills, spawn and then disperse. There is some evidence that the comparable dispersal from the Spawning Box, further along the Rise, is *en masse*, since large catches have been made on the flat at the end of spawning and well afterwards. In the 1999 study of variability on Graveyard (Bull et al. 2001) there was no significant diel variation but there was a 'spike' in the biomass towards the end of the spawning period suggesting that there was some turnover on the hill at that time. In contrast, the associated study of turnover based on spawning state (Doonan et al. 2000) showed no evidence of significant turnover. A complication with the estimates on the hill is that there was substantial bottom shadowing in some places so the spike could have been related to fish moving to the top of the hill. Given the detection level for turnover in Doonan et al. (2000), there could still have been some exchange of fish between the hill and the surrounding flat.

To tackle both spatial and the broader temporal issues we repetitively mapped roughy biomass in an area around and including three hills over the latter part of the spawning season. To monitor the hills we used an acoustic survey covering Graveyard (as the main hill), Scroll and Zombie. The surrounding flat was surveyed by trawling. Since this was a mapping exercise, the trawl survey was based on a set of nominally uniformly spaced grids in which randomly selected cells were trawled in a sequence of repetitions ('snapshots'). The initial snapshots were used to detect the location of fish that had migrated from the hills and to set the survey boundaries. An attempt was made to estimate an upper limit to the roughy trawl catchability by comparing the amount of fish estimated to have been on the hills with that estimated from trawling the migrating fish on the flat.

Since we were attempting to detect and survey dispersing fish, the planned work continued after spawning finished (8 July). This work was combined with data collection from the biomass survey and the results from this and gonad monitoring are reported separately. The gonad development showed that the biomass survey was conducted at peak spawning (running ripe) and mostly spent fish were seen on the flat after about 4 July (Doonan et al. 2003b).

10. METHODS

As noted above, the data were collected as part of a larger biomass survey. Two vessels were used: *Tangaroa* (20 June-20 July 2002) and *Ocean Ranger* (10 July-24 July 2002). All the biomass survey and acoustic work was carried by *Tangaroa* which also did some of the trawling for the mapping. *Ocean Ranger* supported *Tangaroa* with trawling for the mapping.

The data were from the following sources:

- the biomass survey of hills and the surrounding flat,
- additional hill biomass snapshots,
- the migration trawl survey on the flat,
- 'check' trawls outside the grid survey area.

Trawl catches were sampled for species composition and for roughy gonad stages and lengths distributions.

The following analyses were carried out:
1. To detect the time of migration and estimate the flow of fish from the hills on to the flat (uses the main biomass survey and additional data from hills).
2. A classification analysis to identify the numbers of migrating fish in each flat trawl (uses data on spawning stage and length distribution from 'pure' flat and hill trawls).
3. To estimate the relative catchability between the two vessels (uses the trawl grid data).
4. To map the fish migration and area (uses the trawl grid survey data and check tows).
5. To estimate the abundance of the migrating fish on the flat from trawl catches (uses the estimated migrating fish in trawl catches from the grid survey).
6. To estimate trawl-to-absolute scale factor, inverse catchability, $Q=1/q$ (uses the results of calculations from 1 and 5 above).

10.1 Main biomass survey

The main acoustic biomass survey was a stratified random design based on the 1999 survey of the same area (Bull et al. 2000). There were four flat strata and these extended in both directions much further along the Rise than in 1999 (Tables 1 & 2). They were surveyed with acoustic transects aligned in a north–south direction and randomly positioned with respect to longitude. The hills, which were treated as separate strata, were surveyed with systematic 'star' transects (Bull et al. 2000, Doonan et al. 2003a). Hills that had little spawning orange roughy in 1999 (typically deep hills) were omitted (Figure 1). The ratio of the estimated biomass of each of 5 hill to that for the Graveyard were low in an acoustic pilot study in 1997 (median 18%, range 11 to 29% (Bull et al. 1999)) and these remained low in the first proper acoustic survey in 1999 (median 7%, range 1 to 8% (Bull at al. 2000)). There were two snapshots on the hills (22–25 June and 1–4 July) and a single snapshot on the flat (23 June to 8 July).

As is usual in orange roughy stock assessments, the acoustic biomass estimates were taken to be absolute. Echo-integration was used to estimate areal backscatter which was apportioned to different species using the trawling results. Trawls in the flat strata were structured to form a stratified random trawl survey which allowed a semi-independent trawl estimate of biomass to be made. Trawls on hills were targeted and only used for species identification. Acoustic data were collected with NIWA's Computerised Research Echo Sounder Technology. The survey, survey methods and results are described in detail in Doonan et al. (2003b).

Table 1: The main hill biomass survey showing the location, depth of top, and the number of transects and trawls for snapshots 1 and 2.

Name	Hill top			Transects		Trawls	
	Latitude	Longitude	Depth (m)	Snap1	Snap2	Snap1	Snap2
Graveyard	42 45.59	179 59.34 W	750	6	4	2	2
Zombie	42 45.94	179 55.58 W	890	3	3	1	1
Scroll	42 47.15	179 59.86 E	870	3	3	2	1
Deadringer	42 44.14	179 41.42 W	820	3	3	0	2
Morgue	42 43.02	179 57.56 W	890	3	2	0	0

Table 2: The main flat biomass survey showing strata locations, areas, and the total numbers of acoustic transects and random trawls for the single snapshot.

Stratum	Depth range	Longitude range		Area (km^2)	Transects	Trawls
1	840–1150	179 40 E	179 45 W	658	7	6
2	870–1100	179 45 W	178 31 W	1059	4	7
3	840–1075	178 51 E	179 40 E	512	3	4
4	840–1075	178 00 E	178 51 E	444	2	3

10.2 Extended biomass survey

To determine when the roughy dispersed from the hills, the hill acoustic biomass survey was extended in time for a further 16 days. The extended survey focused on Graveyard and the main hills in its immediate vicinity (Zombie, Scroll and Morgue). There were five further snapshots (3–7) in this period on Graveyard, Scroll and Zombie and one on Morgue (during snapshot 3). Snapshot 5 was carried out with a hull-mounted transducer rather than a towed body and is not used in the analysis.

The design and method of estimation was the same as for the hill snapshots 1 and 2. Catch data from Graveyard and Zombie were combined over snapshots 3 to 7. However, there were too few tows on Scroll to allow a split from snapshots 1 and 2 so all its tows were combined and used for all the snapshots, i.e., we assume no change in species composition between the two periods although the backscatter may vary. The numbers of transects and trawls in the additional snapshots are shown in Table 3.

Table 3: The numbers of towed body transects and trawls in the additional hill snapshots. Trawls are assigned to the snapshot nearest in time, but in the biomass calculations they were combined and used for each snapshot here. "–", no data; *a*+*b* means that *Tangaroa* carried out *a* and *Ocean Ranger b* trawls.

Snapshot	Date	Number of transects			Number of tows		
		Graveyard	Scroll	Zombie	Graveyard	Scroll	Zombie
3	9 July	4	3	3	1+0	–	–
4	11 July	4	–	–	1+0	–	0+1
5*	13 July	–	–	–	–	0+1	–
6	16 July	4	–	–	0+1	–	–
7	19 July	2	2	2	0+2	–	0+1
Total tows					5	1	2

* Hull transducer

To estimate the time of the peak of the out-migration, a logistic curve was fitted to the Graveyard biomass estimates, using weighted least squares. The weights were the inverse of the variance for each estimate from the transect variability only. This formulation implicitly assumes that migration occurred in one continuous 'pulse' with smooth changes in migration rate that built to a maximum and then declined. The biomass at time t, $B(t)$, is given by:

$$B2 + \frac{B1 - B2}{1 - e^{c(t-t0)}}$$

where $B1$ is the biomass before migration, $B2$ the biomass afterwards, $t0$ the mid-point of the migration, and c is a parameter that controls the duration of the migration. The more negative c is, the shorter the duration. The time a hill snapshot took place was taken to be d+0.5, where d is the number of days after 30 June, hence snapshots in June were zero or had negative times. The daily quantity of fish migrating at day d (an integer) is given by: $B(d) - B(d+1)$. The variability of the fit was assessed by parametric bootstrapping where the biomass estimates were assumed to have a normal distribution.

10.3 Migration trawl survey

We postulated that at the end of spawning there is a flood of roughy from the hills out on to the surrounding flats moving either to the east or to the west or perhaps in both directions. The roughy then disperse into deeper water as happens after spawning in the Spawning Box, further to the east of the Graveyard on the Chatham Rise.

This idea was investigated by means of a trawl survey. This was based on a one nautical mile grid laid out over the flat ground around Graveyard. The grid was sampled in a series of snapshots in each of which some 'check' trawls were first made to establish the boundaries of the area within the grid to be surveyed. The grid cells to be trawled were selected at random from cells within the boundaries established. As far as possible, any particular trawl was kept within the bounds of its selected cell. To prevent tows being in adjacent cells in the same snapshot, the grid was divided into two parts made up of alternative cells. Grid cells were then all selected from one part for each snapshot, and the choice of which part to use was alternated between consecutive snapshots. Trawls were 1.5 nautical miles long and the towing speed was 3 knots. To avoid confusion with the main biomass survey, grid snapshots are hereafter just referred to as grid 1, grid 2, etc.

Crucial to the survey was the ability to distinguish between resident background roughy and the migrants. The usual background catch of roughy for a 1.5 nautical mile trawl is about 40 kg. However, based on experience from the Spawning Box we expected catches of 1–8 t from the migrating fish and the latter would therefore be easy to detect. Background fish would also be an insignificant component of this and could be ignored. What was actually found was that catch rates of migratory fish were much lower and a method for explicitly distinguishing between catches of background and migratory fish had to be devised. This is described in Section 10.4 below.

The check trawls were made at increasing distances from Graveyard until background catches were obtained. Boundaries were dynamic initially, but were stable by the end of the series. Although not part of the survey, the check tows played an important part in establishing that the survey areas used were adequate.

Both vessels used similar 6-panel, rough-bottom orange roughy trawls for fishing on hills. These have cut-away lower wings, and are based on the development of the 'Arrow' style of trawl that is the industry standard. Codend mesh size was 100 mm. The net has a wing-spread of about 26 m and a headline height of 5–10 m. Catchability was estimated in a conventional manner with respect to swept area and for this the net width was taken to be 26 m.

To assess the relative catchabilities of *Tangaroa* and *Ocean Ranger*, an ANOVA was carried out on the grid trawl data. The same design of net was used on both vessels and a wingtip distance of 26 m was used for all trawls. The data used were $\log_e$ of the roughy total catch rate (kg km^{-1}) in trawls from grids 2–6 that lay in the area of grid 5. The factors tested were the grid snapshot the data came from, an east-west effect within the survey area (boundary at 179° 48.0' E), and the catchability of *Ocean Ranger* compared to *Tangaroa*. The analysis was repeated for trawls with less than 100 kg of roughy and also for those with 100 kg or more. As another check, the relative catchabilities were estimated from the abundances for grids 5 and 6 from each of the *Tangaroa* and *Ocean Ranger* data. Relative catchability was estimated as $B_{Ocean\ Ranger,i} \,/\, B_{Tangaroa,i}$ where $B_{V,i}$ is the abundance for vessel V in grids $i = 5, 6$. Grids 5 and 6 were the only snapshots that had enough trawls from both vessels to do a comparison. The c.v. for the relative catchability estimate was made by parametric bootstrapping assuming the B estimates were normal with variance the same as the estimation variance.

10.4 Estimating the proportion of migrating fish in grid trawls

As outlined above catch rates of migrating fish were much lower than expected and only about 5 times that for background fish rather than more than 30 times. Catches containing migrating fish and the larger catches of what are thought to be 'pure' background fish overlap in the 100 to 200 kg range. The proportion of migratory fish in the mixture was estimated with a classification analysis using as training data, the length distributions of spawning and non-spawning fish from pure background tows to characterise the residents and hill tows for the migrants. The training data came from the biomass survey together with data from the 1999 survey. Some other pure background data were available from check trawls that were well away from the general area where migrating fish were found. The procedure was 'tuned' such that the proportion of migrating fish was zero in almost all the pure background trawls. The procedure was thus conservative in estimating migratory fish, which supported the aim of making the estimate of Q an upper limit. Details of the analyses and results are given in Appendix 1.

The practical result of splitting the grid catches into migrant and background fish was that the proportion of spawning fish assigned to the background category decreased as their catch increased. When the catch of spawners was below 31 kg, all fish were categorised as background. Once the spawner catch reached 80 kg or more, a constant amount (about 15 kg) was assigned to the background. All non-spawners were assigned to the background. Most grid tows had low catches of spawning fish (Figure 2) and so most had no, or low proportions, of predicted migrant fish.

10.5 Mapping migration

As a first step, the migrant catch-rates were extracted from all the post-spawning flat trawl data and these were mapped. For this, latitude and longitude were converted to distances. From this plot there was an obvious "stream" of migrating fish following an east-west axis. A smooth spline, weighted by the catch of migrant fish, was used to estimate the line of this axis. A boundary contour line around this axis was fitted by eye using a catch-rate of 30 kg/tow as a threshold.

The distribution of migrants within the grid snapshot boundary was then estimated along this axis (i.e., a one dimensional east-west plot) for each snapshot, again using a smoothing spline. Snapshots with limited data were combined with others.

10.6 Estimating Q

Biomass indices from trawl surveys, T, are usually related to absolute abundance, B, by $T = qB$, where q is the catchabillity coefficient. The reverse of this formulation is $B = QT$, where $Q = 1/q$, is the scale-up factor to absolute biomass for trawl surveys.

The estimator used was $Q = \Delta B / T$, where ΔB is the absolute biomass that migrates from the hills onto the flat, as estimated by acoustic surveys, and T is the trawl survey estimate of migrant fish on the flat. An estimate of T was made for each grid snapshot by scaling up the catch of migrants using the area swept by the trawl and the overall area considered in the snapshot.

The variance of Q was estimated using parametric bootstrapping and assuming that ΔB and T were normally distributed. The standard error for ΔB came from adding the variances of the pre and post-migration biomass estimates and includes the error from sampling variability in the acoustic transects and the catches, as well as that for the target strengths of orange roughy and other species (Doonan et al 1999). The standard error for T was estimated from standard stratified survey theory.

Since there was some doubt that the grid survey included all the migrating fish on the flat, T was viewed as biased low leading to Q being an over-estimate. Hence, Q was considered an upper limit estimate and consequently the method of estimating migrant fish in the grid trawl catches was deliberately biased in favour of assigning fish to the background group to make sure that no background fish would be classified as migrants.

Q on the flat was also estimated from the main survey (Doonan et al. 2003b, Table 7) using the estimates of spawning biomass from acoustics (22 000 t) and trawling (933 t). Q in this case was thus about 23.

11. RESULTS

11.1 Hill biomass time series

Abundance on Graveyard was high for the first two snapshots of the extended biomass survey, declined in snapshot 3, and levelled out for snapshots 4 to 7 (Table 4). The difference between the abundances in snapshots 3 and 7 was not statistically significant, nor was it between snapshots 3 and 2. Thus, snapshot 3 was intermediate between the earlier snapshots and the later ones and the overall pattern suggested an out-migration that started between snapshots 2 and 3 and was finished by snapshot 4 or 5.

Table 4: Orange roughy abundance (t) and c.v. (%) by snapshot for the Graveyard, Scroll, and Zombie, and the total abundance over all three seamounts. "c.v. trans", the c.v. for just the variability of the backscatter over the transect. "–", no survey. Snapshot 5 was carried out with a hull-mounted transducer rather than a towed body and was not used in the analysis.

	Central	Graveyard			Scroll		Zombie		Total	
	date	(t)	c.v.	c.v. tran	(t)	c.v.	(t)	c.v.	(t)	c.v.
Snapshot 1	23 June	5 600	28	25	190	43	560	84	6 400	27
Snapshot 2	3 July	5 700	24	17	230	32	230	80	6 200	23
Snapshot 3	9 July	2 500	26	18	93	51	150	30	2 800	24
Snapshot 4	11 July	1 900	46	38	-	-	-	-	-	-
Snapshot 6	16 July	1 400	38	31	-	-	-	-	-	-
Snapshot 7	19 July	1 800	27	35	480	59	300	57	2 600	22

The Graveyard abundances are plotted in Figure 3 together with the fitted logistic curve. The latter gives a mid-point for the out-migration of day 8.4, which is one day before the third snapshot on 9 July. About 73% of the biomass left Graveyard and the peak outflow was 780 t/day on 8 July (see bell curve in Figure 3). The days on which 500 t or more of roughy left the hill were 6–9 July, representing 60% of the fish that migrated. Days on which 100 t/day or more left spanned 3–11 July. The bootstraps gave a 90% confidence interval for $t0$ of 3.8–9.5 days, so the mid-point is not that well determined, but most of the bootstrapped logistic curves showed that the migration had finished by snapshot 4. The bootstraps also gave two groups of solutions, one that ranged around the estimated fit (60% of the bootstraps) and another that gave a more intense migration at mid-point 9.1 day (i.e., a peak just before snapshot 3). The alternative solution (dotted line in Figure 3) placed the migration on 8 and 9 July with most fish moving out on 9 July, which is the same day as snapshot 3.

Three snapshots were carried out on Morgue (Table 5), but the trawl data used to apportion the backscatter came from a previous survey in 1999 since this hill is now closed to trawling. The large c.v.s of the first two estimates means that they are not statistically different despite the high abundance of snapshot 2.

Table 5: Orange roughy abundance (t) and c.v. (%) by snapshot for Morgue.

	Central date	Abundance (t)	c.v. (%)
Snapshot 1	23 June	591	81
Snapshot 2	3 July	2132	89
Snapshot 3	9 July	247	35

11.2 Migration grid trawl survey

The significance of the lower than expected catch rates for migrating fish in the grid survey was initially overlooked and this delayed extensions to the survey area. Eventually, it became evident that the catches separated into two groups: low catches that contained a relatively large proportion of small fish and also non-spawning fish, and larger catches in which there was a higher proportion of large fish that were also spawning or spent. The latter catches were characteristically over 100 kg, which was much greater, on average, than the background catches of about 40 kg. The larger catches were associated with mixed migrating and resident fish.

The initial check trawls showed that migrating fish were only to the west of Graveyard and 160 trawls covering eight grid snapshots were completed in this area. The development of the survey area and examples of trawls in some grid snapshots are shown in Figures 4 (grids 1–4), 5 (grids 5–6), and 6 (grids 7–8). The first four established that there was a clear corridor of higher catches (grids 1 to 4) extending 20 nautical miles out to the west from Graveyard. The catches in this corridor averaged about 120 kg and were mostly spent fish. Catches in the background were half those in this corridor and consisted of a range of lengths including small and non-spawning fish. The last four grids covered the whole corridor to the west.

To confirm that the migration was mainly westwards, further check trawls were made to the east of Graveyard after grid 5, but these caught few spawning or spent fish. Consequently, the area in grid 5 was re-surveyed (grid 6). *Ocean Ranger* carried out two final grid snapshots (grids 7 and 8) covering a slightly wider area than grids 5 and 6.

The numbers of successful trawls carried out in each grid snapshot by both vessels, and the biomass from each are summarised in Table 6.

There were 68 trawls in the between-vessel catchability ANOVA. Of these, 26 had catches over, and 42 catches under, 100 kg. Only grids 5 and 6 included data from the western part of the overall grid area. When all 68 trawls were included, no effect was statistically significant at the 5% level. The same result applied for catches under 100 kg. However, for the trawls with catches over 100 kg, the grid snapshot effect was significant, such that grid 6 had about twice the catch rate compared to the others. The relative catchability (*Tangaroa/Ocean Ranger*) was estimated at 1.08 for all the trawls, 1.12 for trawls with catches under 100 kg and 0.90 for those with catches over.

The vessel-specific abundances for grids 5 and 6 gave relative catchabilities of 0.94 (grid 5) and 0.88 (grid 6). The average of the two estimates was 0.91 with a c.v. of 62%, a 90% confidence range of 0.38–1.60, and an inter-quartile range of 0.66–1.11.

Because the numbers of samples for the comparisons were low, the detection power of the tests was also low, and so there were no statistically detectable differences in the catchabilities between the vessels, and the estimated differences were small compared to other sources of error. Hence, for this study we have taken catchability to be the same for both vessels.

Table 6: Abundance, distance of the western boundary from Graveyard, number of trawls (survey and check), number of grid cells, and survey area for the migration trawl survey. 'T' *Tangaroa*; 'OR' *Ocean Ranger*; 'Tot' Total.

Grid	Date	Abundance (t)	c.v. (%)	Western bound (km)	Survey tows Tot	T	OR	Area (km^2)	Number of grid cells	Check tows T	OR
1	10 July	162	51	11	11	11	0	288	76	3	0
2	11 July	207	43	13	16	7	9	201	53	0	2
3	12 July	60	41	13	11	6	5	129	34	2	2
4	13 July	91	73	13	3	0	3	129	34	6	2
5	15 July	172	25	42	25	13	12	276	73	8	5
6	17 July	309	27	42	25	10	15	276	73	3	4
7†	21 July	12	54	42	18	0	18	360	95	0	4
8‡	22 July	24	100	42	10	0	10	360	95	0	0

† Two strata, west and east, with 6 tows in the west stratum
‡ Two strata, west and east, with 3 tows in the west stratum

11.3 Mapping migration

The fitted migration axis is shown in Figure 7 and it can be seen that, once clear of Graveyard, it runs in a westerly direction. The area enclosing most of the migrating fish has two parts: a rather convoluted area just west of Graveyard between 1025 and 1200 m, which may be a 'marshalling' area, and a corridor stretching to the west between 1000 and 1100 m (Figure 7). A few tows with migrants in them are outside these two areas, but their catches are small and are isolated amongst many trawls that caught no migrants. We conclude that there is indeed a post-spawning migration from the hills, and that the fish travel west in a fairly narrow corridor. However, there is a possibility that some fish are dispersing into deeper water (dotted line ending ? in Figure 7).

The plots in Figure 8 show the densities of migrating fish by longitude (which approximates the axis) and grid snapshot and suggest that there were two migration pulses. Data were combined over the grid snapshots to allow smoothing giving 5 periods:

A. Grids 1–2, midpoint 10–11 July;
B. Grids 3–4, midpoint 12–13 July;
C. Grid 5, midpoint 15 July;
D. Grid 6, midpoint 17 July;
E. Grids 7–8, midpoint 21–22 July.

The first pulse appears in period A, it has moved west in B and dissipated somewhat in C with some remaining fish to the west in period D (Figure 8). The pulsed nature of the movement is best seen to the east between Figures 8A and 8B where catch rates decline from 150 kg/km to about 25. Although catch rates have dropped right down to the east in Figure 8B, they are up at 150 kg/km in the west and the trailing edge of the pulse (50% of the peak amplitude) appears to be at longitude 179.838. The lower catch rates in the west in Figures 8C and 8D suggest that the wave of fish moved west of longitude 179.5 in one or other of these periods.

The second pulse appears to the east in period D (Figure 8D) and has a clear leading edge at longitude 179.873. By period E, 4–5 days later, there are few traces of migrating fish (Figure 8E).

Table 7: Biomass of migrating fish in the eastern part of the area of grid 6 (east of 179 51 E) and t-tests between successive periods. Date is the median day in July for the tows in the group.

Period	Number of trawls	Biomass (t)	c.v. (%)	Date	Test	Significant at 5%?
A	11	168	30	11.5	A vs B	Yes
B	11	57	35	13	B vs C	No
C	10	26	58	15	C vs D	Yes
D	12	176	25	18	D vs E	Yes
E	12	15	56	20	–	–

The two-pulse hypothesis was explored further by comparing catch rates between periods for the area just east of Graveyard. The area considered was the eastern part of grids 5 and 6 with a western boundary at longitude 179 51 W, 13 km west of Graveyard, and an area of 91 km^2. Apart from one cell, this area was within all grid snapshots. Trawls were grouped into time periods in the same way as above to give enough data for comparisons. Successive periods were compared with t-tests, which were significant (at the 5% level) between A and B, C and D, and D and E, but not between B and C (Table 7). Thus, a pulse was present in periods A and D, but absent in B, C, and E.

This comparison was considered in an alternative way by comparing the relative biomass in cells that were sampled in all of the grid snapshots. The cells were all from the eastern area as above, but only cells with two or more trawls were used. Densities were normalised within cells by dividing by the mean density within the cell. The results are plotted against time in Figure 9 together with fitted lines and again show two clear peaks, the first on 10–11 July and the second on 18 July. The lines were fitted using a GAM (smoothing) regression incorporating splines, on the log of the relative densities plus one. The fit for a spline with 5 degrees of freedom (df) was statistically significant at the 1% level and 5 df gave the best statistical fit.

The pulse trailing edge in period B and leading edge in period D (Figure 8) can be used to give an estimate of migration speed. Assuming that the trailing edge was at Graveyard at the end of period A (12 July) and at longitude 179.838 a day later on 13 July, then the speed is about 13 km/day. If the trailing edge moves off to the western boundary in period C (15 July, 2 days later), the speed is 14 km/day. However, it may not have reached the boundary for another two days, during period D (17 July), in which case the speed would be 7 km/day. Similarly, if we assume that the leading edge was at longitude 179.873 on 17 July and moved off to the west in period E (21.5 July), the speed is 7 km/day. The mean of these estimates is either 9 or 11 km/day, depending on the period in which the trailing edge disappears. Given the approximate nature of the calculations, we have not estimated the variance

11.4 Estimating *Q*

ΔB, the biomass that migrates from the hills onto the flats, was estimated by subtracting the biomass left on the hills after migration from the biomass before migration. The latter was taken to be the average of biomass snapshots 1 and 2 combined over Graveyard, Scroll, and Zombie (Table 3), which was 6264 t (c.v. 17%). The abundance on the hills after the migration was estimated from biomass snapshots 4, 6, and 7 on Graveyard and snapshot 7 on Scroll and Zombie, and was 2489 t (c.v. 20%) and ΔB was therefore 3775 t(c.v. 25%). The before and after migration biomasses are statistically significantly different at the 1% level (t-test value of 3.2). From the logistic fit to the migration in Section 11.1 above, the proportion of bootstrap runs in which less than 20% of the migration occurred on or before the day of snapshot 2, was 80%. This means that there is some chance that migration started before snapshot 2 in which case our estimate of the before migration biomass would be too low. Turning to the question of when all the fish had left the hills, for 94% of the bootstrap runs, at least 80% had left by the day of snapshot 4. Thus there is a small change that our estimate of the post-migration biomass is too high. Both of these possibilities have been ignored in our analysis.

Morgue was not included above because its status is uncertain. In the 1999 survey Morgue had only a modest acoustic mark and a small spawning biomass of roughy with a significant proportion of smooth oreos. However, in this survey, a very large acoustic mark was found but since the hill is closed to fishing, it's catch composition could not be estimated directly. Therefore, the 1999 catch composition was used to estimate the biomass, which was quite substantial (Table 5). We have therefore made an alternative estimate of ΔB including the fish on Morgue. The latter was the mean of snapshots 1 and 2 (1312 t, c.v. 75%) minus snapshot 3 which gives 1065 t (c.v. 92%) and the alternative ΔB was 4840 (c.v. 28%). A problem with the Morgue estimate is the very large c.v. such that the migrating amount is not statistically different from zero.

The estimate of T (trawl biomass on the flat) depends on whether one or two migration pulses took place. If there were two pulses, the first pulse is estimated by the mean of grids 1 and 2 (Table 6), which is 184 (c.v. 33%), and the second pulse is in the eastern part of grid 6 during period D, which is 176 t (c.v. 25%) (Table 7). The sum of these is 360 t (c.v. 21%). In the case of a single migration pulse, T is 241 t (c.v. 20%) which is estimated from the mean of grids 5 and 6. These grids covered a larger area that grids 1–4, and in grids 7 and 8, the fish had clearly moved away.

We consider the 'best' estimates of pre and post-migration biomass to be those excluding Morgue and using two migration pulses. This gives a Q of 10.5 (c.v. 36%) with 95% confidence limits of 5 to 20. From this, catchability, q, is 9.5% with 95% confidence limits of 5% to 20%. Alternative estimates using the different combinations of one and two migration pulses and with and without Morgue's biomass are:

Two pulses, including Morgue:	$Q = 13$ (c.v. 38%)
One pulse excluding Morgue:	$Q = 16$ (c.v. 36%)
One pulse including Morgue:	$Q = 20$ (c.v. 37%)

12. DISCUSSION

The spatial distribution of spent fish on the flat in the period after fish disappeared from the hills strongly suggests a westward migration pattern in quite a narrow depth corridor away from the spawning hills (notably Graveyard). It is probable that they initially gather in a 'marshalling' area just west of the base of the hills immediately around Graveyard. Although the density of migrating fish was lower than in the out-migration from the Spawning Box, the differences in length and gonad stages of fish on the hills on the flat during the main part of spawning clearly distinguish the two classes of roughy and allow migrants to be identified.

Coburn & Doonan (1994) estimate the migration rate from the spawning plumes in the Spawning Box to be about 10 km/day (which is about 0.3 body lengths per second) once the main mass of fish has cleared the spawning area. This result is derived from the positions of good catches from blind fishing on a 'block' of fish travelling east. Trawls too far east or west of the block gave very small catches and this effect continued for about 150 km. The migration speeds estimated here at 9–11 km/day are very close to those from the Spawning Box.

The logistic fits to the variation of Graveyard biomass with time show that the migration could have taken 9 days at flows over 100 t/day, or might have taken only 2 days. Taking the migration rate to be 10 km/day, assuming a single pulse, and ignoring any delays whilst fish gathered in the marshalling area, then for the 9-day migration, which peaked on 8 July, the centre of the pulse would have been 20 km away from Graveyard at the time of the first grid snapshot. For the 2-day migration, it would have been 10 km away. By the time of grid 5 the distances would have been 70 and 60 km respectively and by 20 July (just before grid 7), 120 and 110 km. The latter are both well outside of the area surveyed in the last grid. In the case of earlier grids, the western limit for the first four grids was 13 km, and for the last four grids, it was 42 km (Table 6), so even for the earlier part of the migration survey, we cannot be sure that all the migrating fish were in the area surveyed. Clearly, the estimate of Q should be viewed as an upper limit.

Of course, the above assumes that the migration speed was 10 km/day right from the start and that the migration was only one pulse, which maintained its coherence as it travelled on the flat. This does not necessarily mean that the fish were continuous and they could have been in a cluster of many small schools in which the inter-school distance was similar (in the case of the 2 day pulse) or varied smoothly from a large distance at the start (for example when 100 t/day left Graveyard) to a small one at the peak (when 780 t/ day left) and then increased again.

The simple logistic model seems too simple since two pulses were detected in the grid survey. The first pulse was already present on 10 and 11 July and as the leading edge was at the western boundary, it must have started by 9 July which is consistent with the logistic fit. The leading edge of the second pulse again was about 10 km away and so might be expected to have begun on 16 July which is inconsistent with the logistic model. It is possible that fish may be disappearing from the acoustic surveys on the hills, but there is a lag before they appear in the trawls on the flat (including the marshalling area). In this case the fish could be hard down on the sides of the hills and so be in the acoustic shadow zone. To be consistent with the results, the lag must be of the order of 4 to 7 days. With a 7-day lag for example, the first pulse would have started on 2 July, which is just plausible. Alternatively, the migration from the tops of the hills splits into two parts with the second part remaining undetected for 7 days.

Out-migration seems to have occurred later in 2001 than in 1999, since in 1999, the last survey on Graveyard was on 9 July and this did not indicate any outward migration of fish (Doonan et al. 2000). Scientific observer data show that most fish had departed by 17 July.

The estimate of Q of 23 from the main biomass survey is at the top end of the confidence limit in section 11.4 above for the 'best' upper limit (two pulses and excluding Morgue). However, it is about the same as the maximum Q in the alternative estimates. Although most fishing takes place on hills, 70% of the spawning orange roughy abundance was on the flat, so a realistic limit on the flat estimate is of considerable importance to the overall estimate of abundance. These results suggest that either the vulnerability of orange roughy to trawls on the flat is very low (only 4% are caught in the worst case) or the acoustic biomass is an overestimate or both.

The method used for generating the acoustic biomass estimate for the flat contains some strong assumptions, which if not met, could introduce large biases. These include assumptions that the estimated target strengths for all the species in the mix are correct, that all species are equally likely to be caught in the trawl, and that the height above the bottom over which acoustic backscatter was integrated was correct. Orange roughy are particularly sensitive to errors in the proportions of the other species since they have a low target strength compared to the others which mostly have air bladders. Although orange roughy are larger than most of the other fish and make up to 40% of the catches by weight, they only make up a small part of the acoustic backscatter. We have no real idea about the biases in the acoustic method as applied to the flat so an estimate of Q would provide a check and would also allow trawl survey relative biomass to be made absolute.

13. CONCLUSIONS

13.1 Migration

Specific conclusions about the 2003 spawning are:

- At the end of spawning, just after 3 July, spent fish began to move off Graveyard.
- The outflow of fish peaked on 8 or 9 July.
- After a lag of 4–7 days the fish appeared on the flat to the west, at the base of the hills.
- Once on the flat, the spent fish moved westwards within a corridor between 1000–1100 m deep, at about 10 km/day.
- Approximately 60% of the spawning fish moved off the hill; the remainder were assumed to be hill residents.

The dates for spawning's end and peak outflow, the lag length, and the ratio of resident to migratory fish may differ each year.

13.2 Catchability

Trawl catchability, q, on the flat has a lower limit of 10% with a 95% confidence interval of 5–20%. The relative catchabilities of the two vessels, *Tangaroa* and *Ocean Ranger*, using the same trawl gear and rigging, were very similar, but the precision of this is low and they could actually differ by as much a factor of two.

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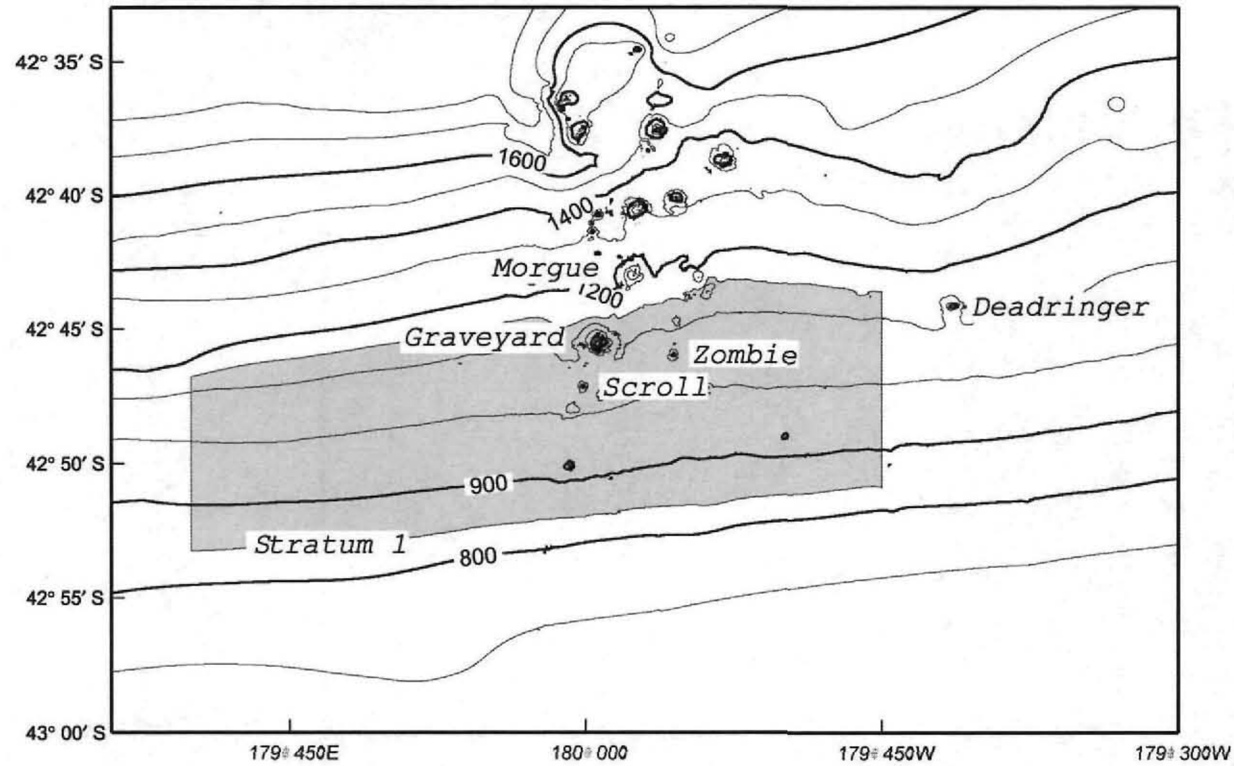

Figure 1: Graveyard area survey: central flat stratum (stratum 1) and hills surveyed.

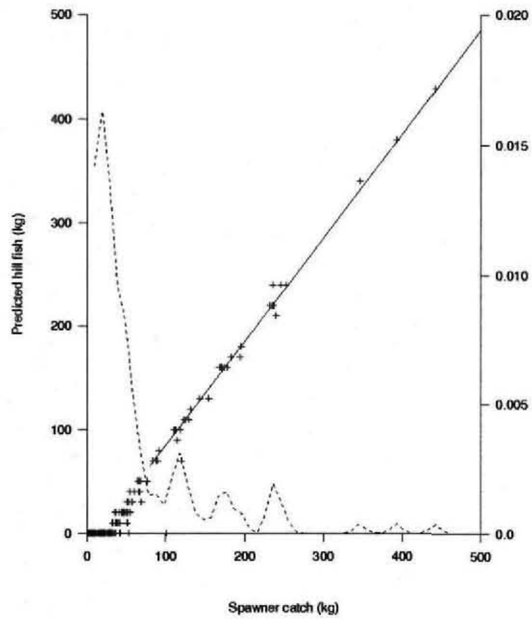

Figure 2: Trawl catches on the flat. Weight of migrants in flat catches predicted by the classification analysis (left y-axis) vs. spawning fish catch. Solid line has a slope of one and intercept of 15 kg. All non-spawning fish were assigned to the background. Dotted curve is the distribution of catches of spawning fish in flat tow (right hand axis shows the frequency).

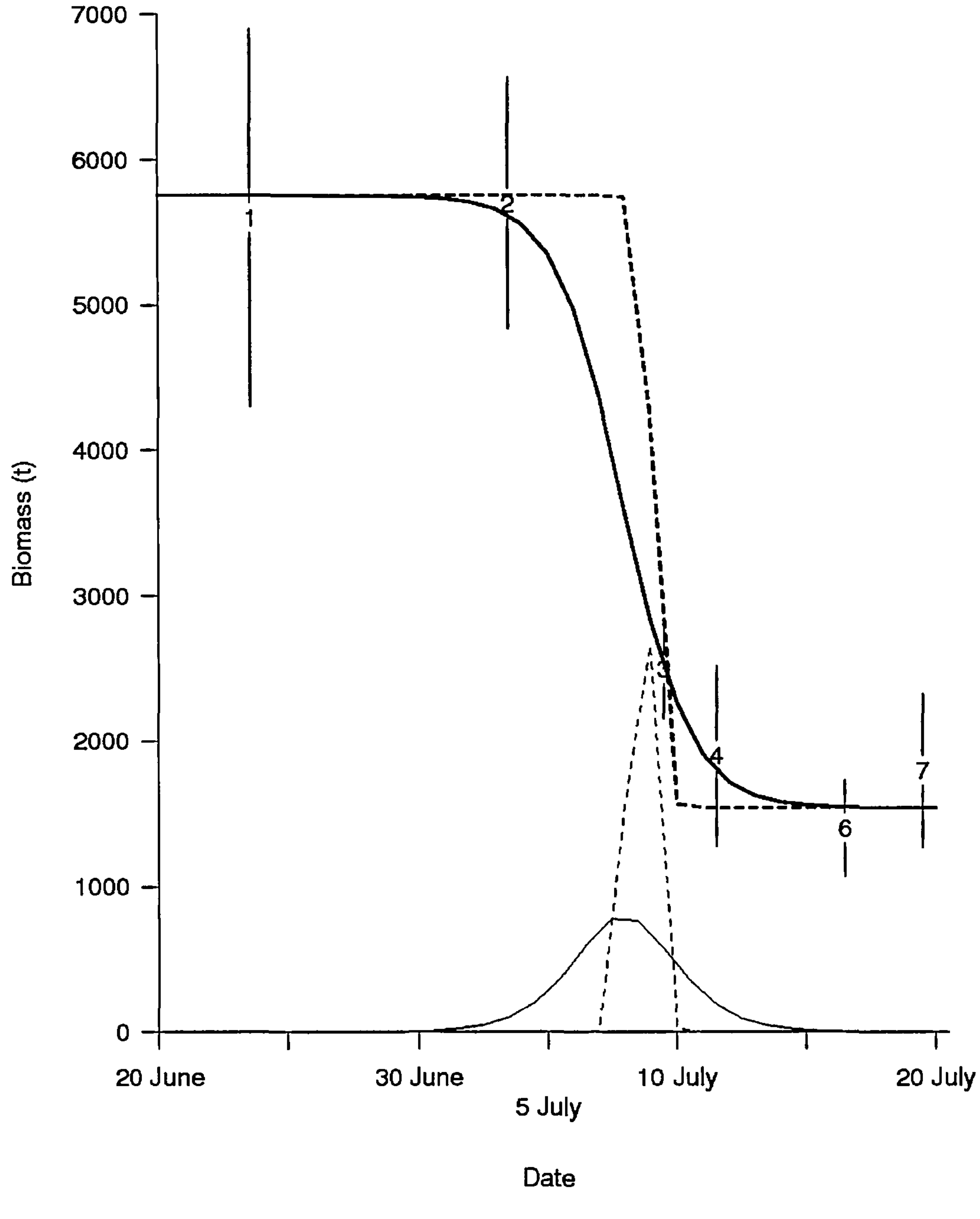

Figure 3: Graveyard out-migration. Biomass estimates and one standard error from each snapshot (1, 2, 3, 4, 6, and 7) with the fitted logistic curve for the biomass trajectory (solid curve). Solid bell curve is the fitted daily migration amounts. An alternative estimate that occurred in 40% of the bootstrap runs is shown as dotted lines.

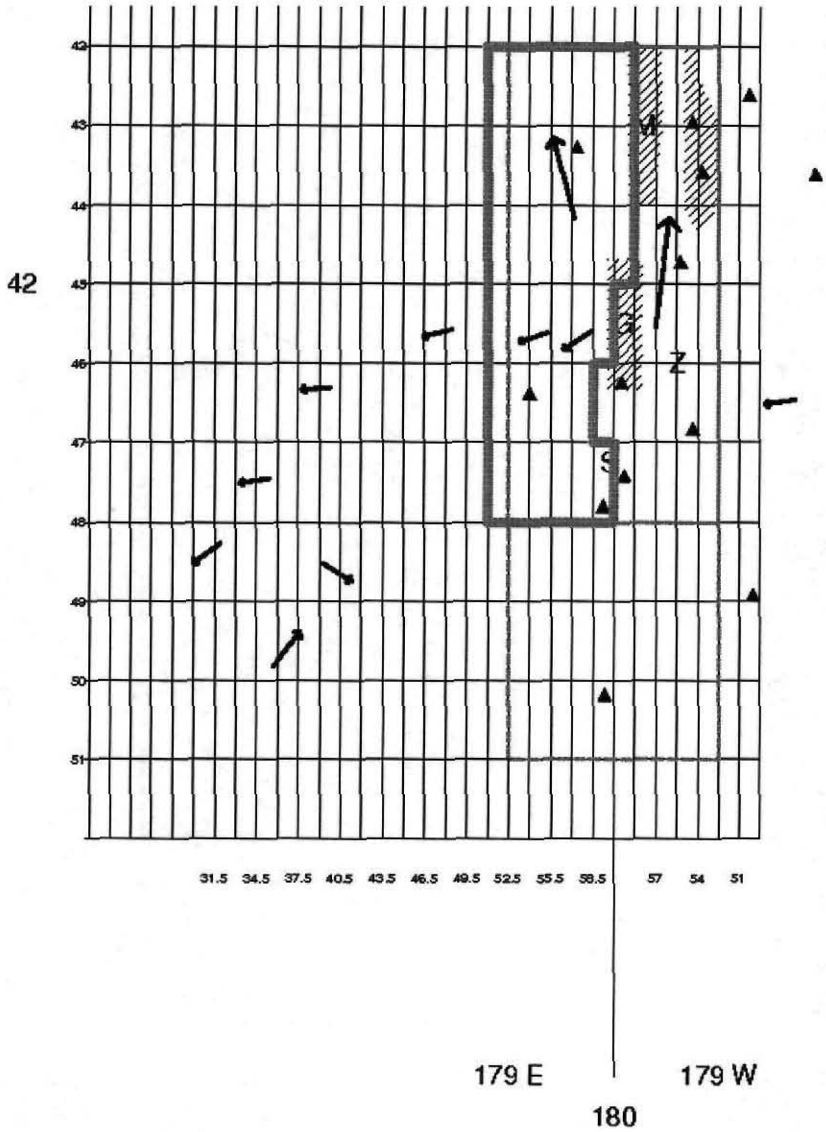

Figure 4: Grid and survey area for grids 1–4. Hatched areas are hill bases for Graveyard (G) and Morgue (M) or a closed area. Additional named hills are Scroll (S) and Zombie (Z). Other hills are indicated by triangles. The thin faded line is the boundary for grid 1; the thin faded dotted line, grid 2; and the thick faded line, grids 3 and 4. Arrows are trawl tracks for grid 4. Note the background grid pattern shows the overall grid survey area whilst the thicker lines detailed above show the actual areas of each of the listed grids.

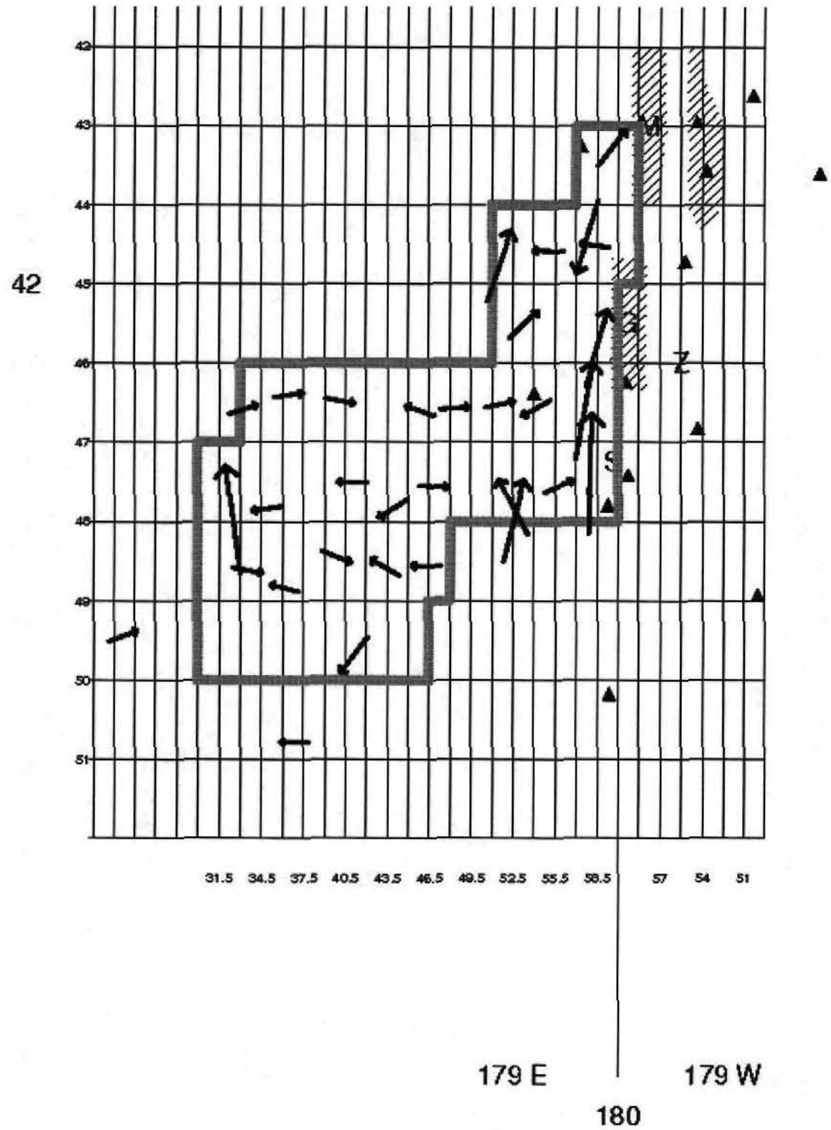

Figure 5: Survey area for grids 5 and 6. Hatched areas are hill bases for Graveyard (G) and Morgue (M) or a closed area. Additional named hills are Scroll (S) and Zombie (Z). Other hills are indicated by triangles. The thick faded line is the boundary for grids 5 and 6. Arrows are trawl tracks for grid 6. Note the background grid pattern shows the overall grid survey area whilst the thicker lines detailed above show the actual areas of each of the listed grids.

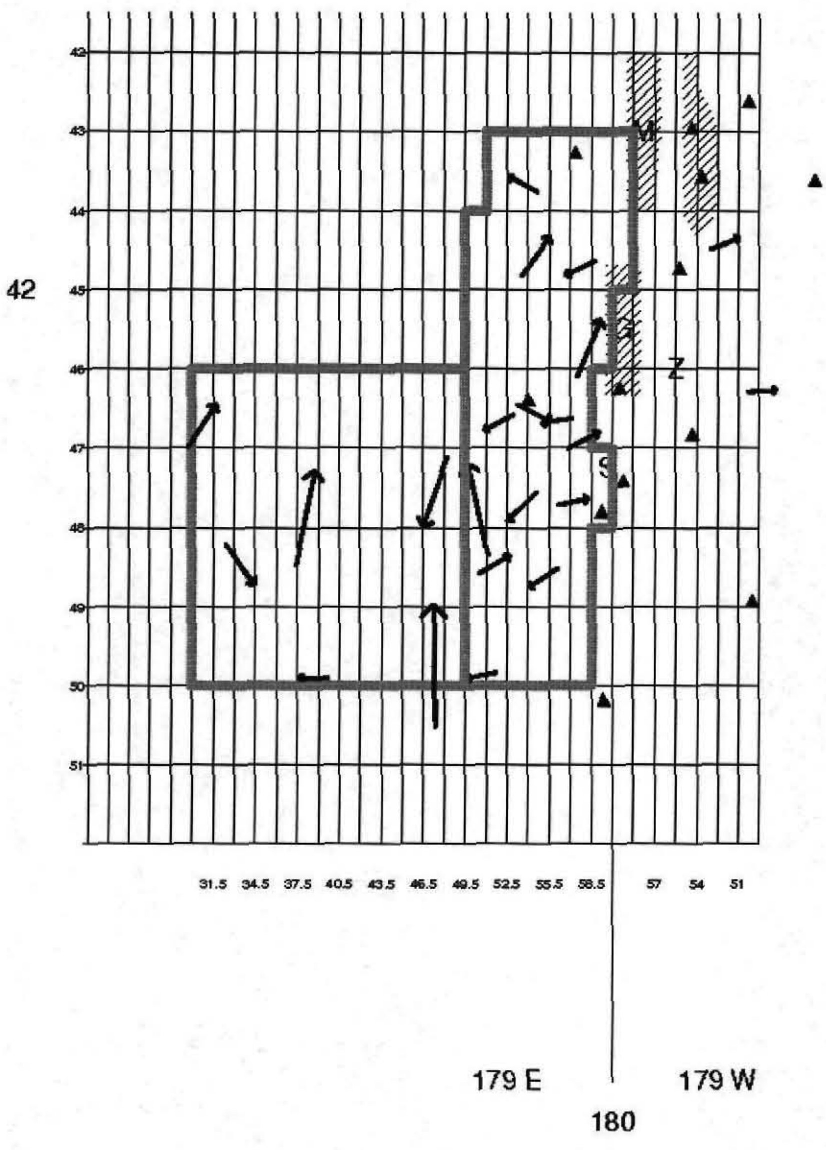

Figure 6: **Survey area for grids 7 and 8. Hatched areas are hill bases for Graveyard (G) and Morgue (M) or a closed area. Additional named hills are Scroll (S) and Zombie (Z). Other hills are indicated by triangles. The thick faded line shows the two boundaries for grids 7 and 8. Arrows are trawl tracks for grid 7. Note the background grid pattern shows the overall grid survey area whilst the thicker lines detailed above show the actual areas of each of the listed grids.**

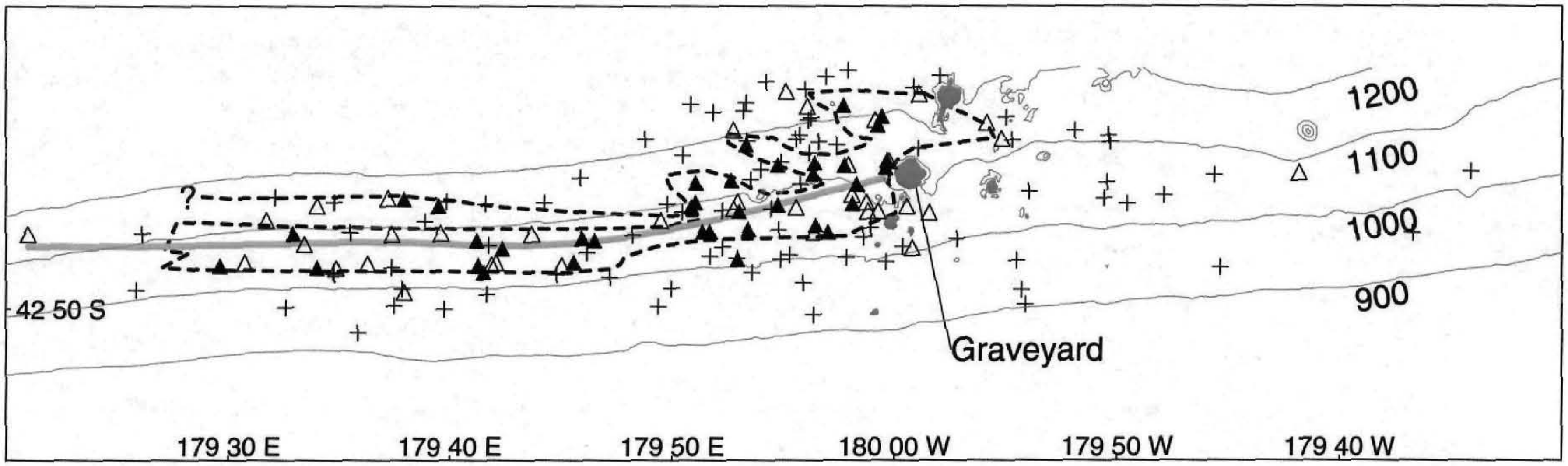

Figure 7: **Graveyard area, distribution of migrating fish on the flat. Catches over 55 kg (filled triangles), catches below 55 kg (triangles), and zero catch (cross). The wide faded line running east-west between the 1000 and 1100 m contours is the axis of migration. The dotted lines immediately above and below delimit the north-south spread of migrants. The second dotted line north of the axis (ending with ?) is an alternative northern boundary. Bases of hills are shaded areas.**

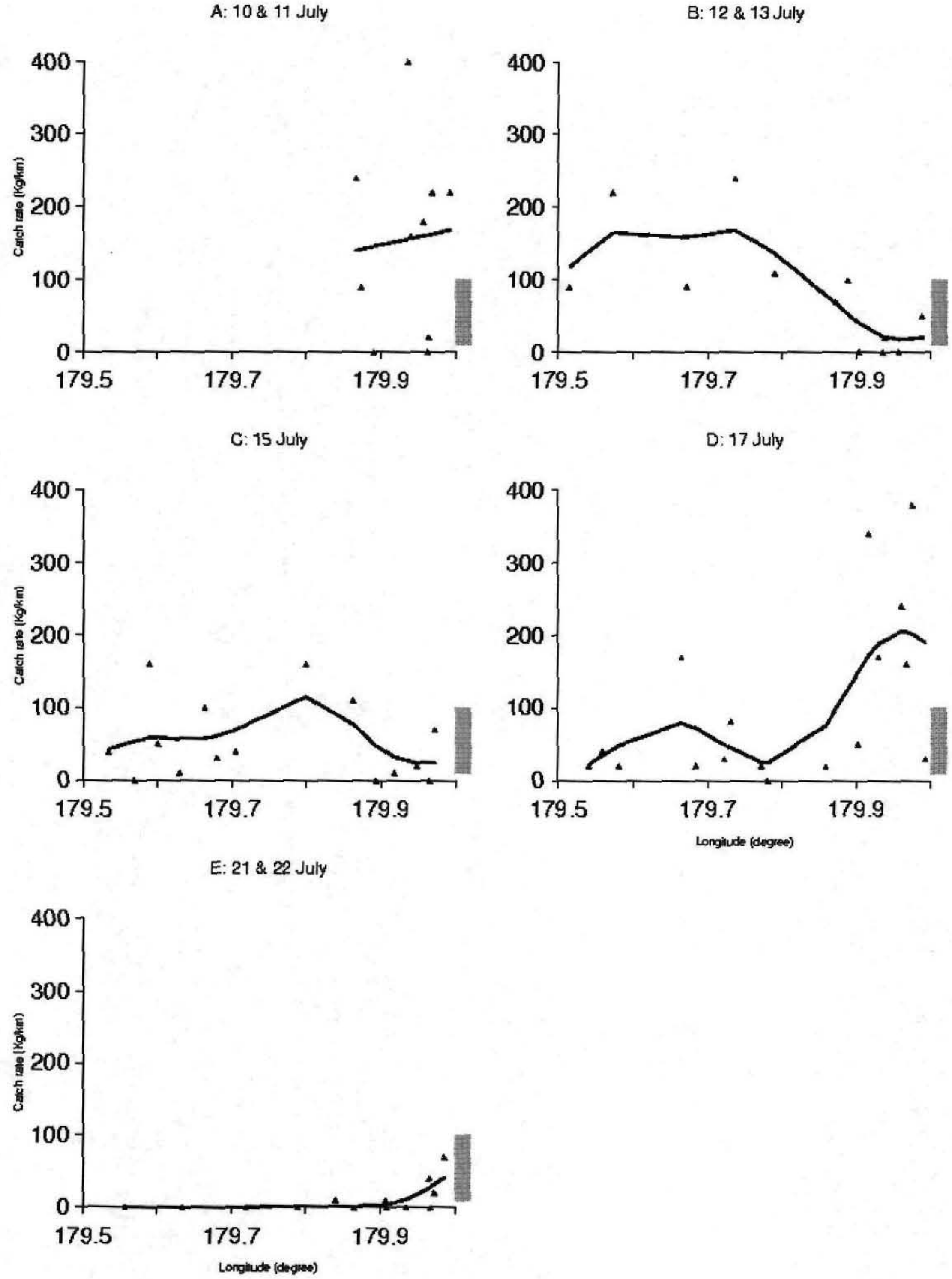

Figure 8: **Density of migrating fish by longitude for fish within the migration corridor. Migration is westwards. The position of Graveyard's base is shown by the grey block. The lines are smoothing splines through the data. A: grids 1 and 2; B: grids 2 and 3; C: grid 4; D: grid 5; E: grids 7 and 8.**

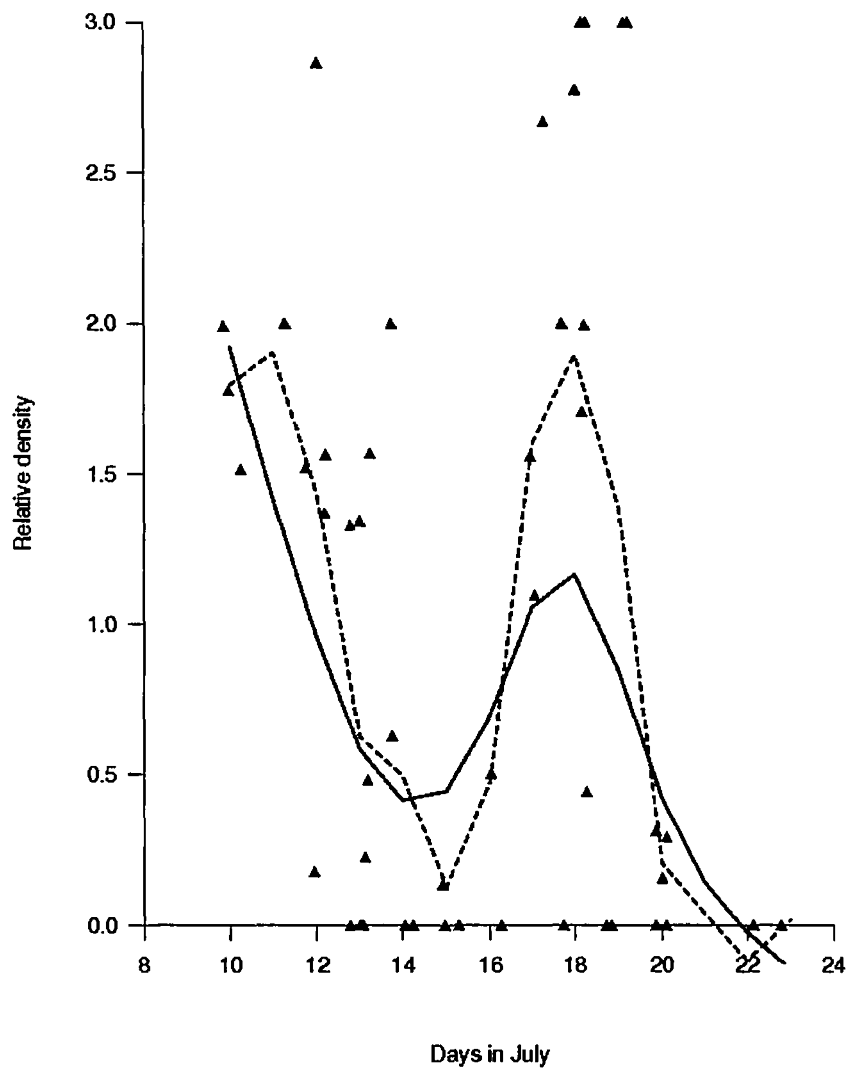

Figure 9: **Relative density of migrating orange roughy by day in July for grid cells that had two or more trawls in them. The estimated fitted line (spline, 5 df) for all data is the solid line; the dotted line is a smoothing spline with 10 df. Day values have been displaced in some instances so that all points are visible.**

APPENDIX 1

Estimating spawning fish from the hills (migrating fish) in trawl catches on the flat

Two training data sets were made up from the 1999 and 2002 surveys. Each set had data both from flat trawls that caught only background fish and hill trawls that caught only spawning fish. Defining distributions that characterised the catch were estimated for both background and hill fish for each of the two training sets. These defining distributions were used to predict the proportions of hill and background fish in catches where both hill and background fish were present. To select which distribution to use, the 1999 distributions were used on the 2002 training data and the errors recorded. Similarly, the 2002 distributions were used on the 1999 training data set. The one with the lowest error rates was chosen. The variables used are in Table A1.

A1. Data

The selected trawls were from the main spawning period and were from the main biomass survey so they were considered representative of the hill and background distributions. There were 23 flat trawls and 26 hill trawls in the 1999 data. In the 2002 data there were 16 flat trawls and 20 hill trawls. The hill trawls in both cases were on Graveyard, Scroll, and Zombie.

The data consisted of numbers in the catch by length class for spawning and non-spawning fish. Data for male and female were combined. Spawning fish were defined as those with a gonad stage of 3 or more and non-spawners a gonad stage of 1 or 2.

A2. Non-spawning fish relationships

Hill fish are always greater than 23 cm in length and any fish less than this were always classified as background ($NS_{23,bg}$). The numbers of non-spawning fish of 24 cm or more (NS_{24}) were moderately correlated with $NS_{23,bg}$ and had a normal distribution. The length frequencies of the NS_{24} for the hills were different from the background so that the length frequencies of these fish can be used to partially separate hill fish in the flat catches. The proportion of non-spawning fish in hill catches is exponentially distributed.

A3. Spawning and spawned fish relationships

The length frequencies of spawning fish in the background are similar to those on the spawning on the hills so length frequency was of little use in separating these two types. The only relationship found was that the number of spawners in the background catches is correlated with $NS_{23,bg}$ and so a linear regression can be used.

A4. Estimating out-migrating fish density on the flat

The above relationships were used to predict the number of migrating fish in flat catches via a statistical approach. The defining distributions were turned into a likelihood and data from flat trawls viewed as being from a mixture of background and hill fish, so that the analysis estimated the proportion of hill non-spawners (24 cm or larger) and spawners. Penalty functions were used to shrink the estimated proportions of hill fish to zero.

The parameters were estimated from minimising the following negative log-likelihood:

$$\frac{1}{2}\left(\frac{S_{bg}-\upsilon_1(NS_{23})}{c_1\upsilon_1(NS_{23})}\right)^2+\frac{1}{2}\left(\frac{NS_{bg}-\upsilon_2(NS_{23})}{c_2\upsilon_2(NS_{23})}\right)^2$$

$$+\frac{1}{2}\sum_{i=24}^{39}\left(\frac{\log\left(\frac{\mathrm{pb_i}}{\mathrm{g_i}}\right)}{\sigma_{\mathrm{b,i}}}+0.5\sigma_{\mathrm{b,i}}\right)^2+\frac{1}{2}\sum_{i=24}^{39}\left(\frac{\log\left(\frac{\mathrm{ph_i}}{f_\mathrm{i}}\right)}{\sigma_{\mathrm{h,i}}}+0.5\sigma_{\mathrm{h,i}}\right)^2$$

$$+\lambda_1 ph+\lambda_s ps+\lambda_{ns} pns$$

The penalties, λ_2 and λ_3, were chosen so that all background tows in the training set, except one, were estimated to be have background catches only (i.e., pns=ps=0). The aim was to make sure any true background tows were estimated as such. The consequence is that in tows with a mixture of background and hill fish, the hill component is biased low and this fits with the aim of estimating a minimum hill fish abundance on the flat.

Table A3 shows the outcome of the error comparisons and it can be seen that the 1999 parameter set performed best overall. To mimic the catches encountered in the grid trawl survey in the hill catches, the numbers in the stage-length samples were not scaled up by the sampling fraction, i.e., the sample numbers were used rather than the numbers in the catch. Catches on the flat were much lower than on hills and generally all the roughy in the flat catches were staged and measured. In addition, the 2002 data set was expanded with 3 background tows from the flat survey that were excluded when determining the 2002 distributions.

The predicted numbers of hill fish were converted to weight (t) using the length-weight relationship, weight = $5.96\text{x}10^{-8}$ length $^{2.812}$. These weights were adjusted such that the total weight from the length-weight relationship was the same as the observed weight.

Table A1: **variables used in the analysis.**

Variable	Description
Hill and background distribution variables	
$NS_{23,bg}$	Number of non-spawners, length 23 cm or less. Always assigned to background, i.e., none this small found on the hills.
S_x	Number of spawners in x=bg (background), h (hills). Distribution of S_{bg} is normal, mean $v_1(NS_{23,bg})$ (= $8.0 + 0.32\ NS_{23,bg}$), c.v. c_1 (0.86).
NS_x	Number of non-spawners (length 24 cm or more) in x=bg (background), h (hills). Distribution of NS_{bg} is normal, mean $v_2(NS_{23,bg})$, c.v. c_2 (0.90). See Figure A1 for v_2. which is a smoothing spine with 3.25 df.
g_i	Fraction of NS_{bg} fish in length class i for background fish. Distribution lognormal. See Table A2 for means and c.v.s. The standard deviations in the log scale is $\sigma_{b,i}$
f_i	Fraction of NS_h fish in length class i for hill fish. Distribution lognormal. See Table A2 for means and c.v.s. The standard deviations in the log scale is $\sigma_{h,i}$
Estimated parameters	
ps	Proportion of total numbers of spawners assign as hill fish
pns	Proportion of total numbers of non-spawners, 24 cm or more, assigned as hill fish.
ph	Proportion of non-spawners in the hill catch. Distribution exponential, mean $1/\lambda_1, \lambda_1 = 11.1$.
pb_i	Proportion of background non-spawners (length 24 cm or more) in length class i.
ph_i	Proportion of hill non-spawners (length 24 cm or more) in length class i.
Penalties	
λ_2	Penalty to shrink ps to zero. $\lambda_2 = 6$.
λ_3	Penalty to shrink pns to zero, $\lambda_3 = 0.05$.
Data	
$NSobs_i$	Number of non-spawners in the catch in length class i, i=24–39
Sobs	Total number of spawners in the catch.
$NSobs_{23}$	Total number of non-spawners in the catch, length 23 cm or less

Table A2: **Non-spawner expected length frequency (%) and the c.v. (%) for background and hill fish. The distribution around the expected proportion at each length class is lognormal.**

	Background		Hill	
Length (cm)	g	c.v.	f	c.v.
24	10	69	1	382
25	10	69	2	276
26	11	61	3	217
27	11	62	6	135
28	10	68	8	113
29	11	56	12	65
30	10	68	7	122
31	9	73	13	60
32	6	112	17	41
33	4	145	8	110
34	3	176	9	93
35	2	279	5	157
36	2	286	5	155
37	1	316	3	226
38	1	368	1	309
39	1	442	0	511

Table A3: **Cross comparison of data fits to the 1999 and 2002 data when using the distributional parameters estimated from the 1999 or the 2002 data. For the background, fits are expressed as the number of tows that had some estimated hill fish over the total number of tows tested, and in brackets, the mean error for the tows that had estimated fish in them. For the hill data fits, the mean error (%) is reported.**

		1999 parameters	2002 parameters
1999 data	Background	1/23 (-11%)	10/23 (-65%)
	Hill	-12%	-8%
2002 data	Background	1/19 (-50%)	3/19 (-40%)
	Hill	-11%	-10%

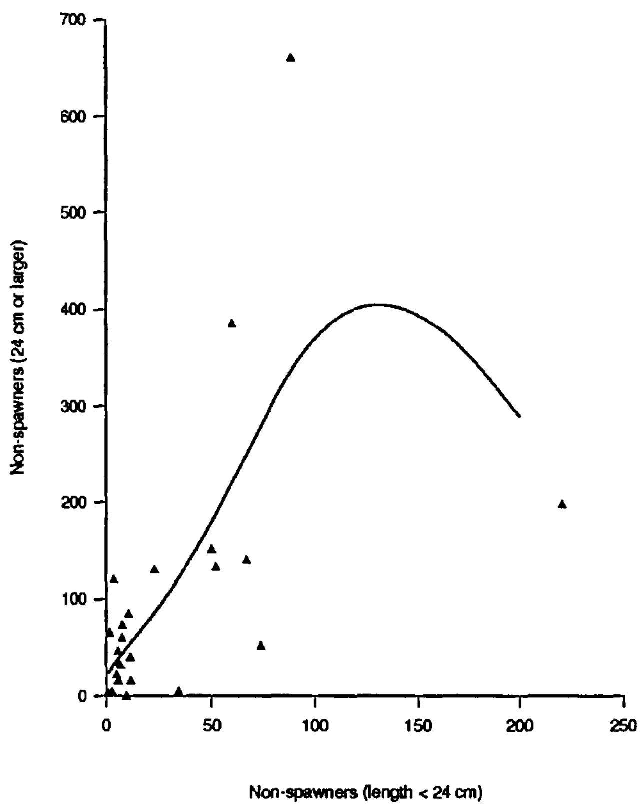

Figure A1: **Background catches: spline regression of total number of non-spawners 24 cm or larger on non-spawners 23 cm or smaller. Estimated using the 1999 training data, shown as triangles.**